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ON THE AGENCY OF

WATER IN VOLCANIC ERUPTIONS;

WITH SOME

OBSERVATIONS ON THE THICKNESS OF THE EARTH'S CRUST FROM A GEOLOGICAL POINT OF VIEW;

AND

ON THE PRIMARY CAUSE OF VOLCANIC ACTION.

BY

JOSEPH PRESTWICH, F.R.S., F.G.S., &c.

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[*From the* PROCEEDINGS OF THE ROYAL SOCIETY, No. 246, 1886.]

"On the Agency of Water in Volcanic Eruptions; with some Observations on the Thickness of the Earth's Crust from a Geological Point of View; and on the Primary Cause of Volcanic Action."* By JOSEPH PRESTWICH, F.R.S., F.G.S., &c. Received March 26. Read April 16, 1885.

[PLATE 1.]

§ 1. *Introductory Observations—Current Hypotheses—The Vapour of Water considered as the Primary Cause of Volcanic Action.*

The important part played by water in volcanic eruptions is a well recognised and established fact, but there is great difference of opinion among geologists as to whether water should be considered the primary or secondary agent, and as to the mode, time, and place of its intervention. The prevailing opinion in this country is that water is the primary cause of volcanic activity. Whichever view may be adopted, the subject is one which is so largely concerned with the laws regulating the underground circulation of water, that the consideration of the two questions must proceed *pari passu*. We shall therefore have to consider somewhat fully the hydro-geological questions relating to the circulation and penetration of water, and in connexion with this the contested question of the probable thickness of the earth's crust from the geological standpoint. The objections to the chemical theory of Davy, according to which, water finds its way to the interior of the earth, and there, meeting with the metals of the earths and alkalies, is decomposed with the evolution of intense heat, steam, and gases, have been so often stated, that it is not necessary here to refer to them further than to remark that the objections I shall have to urge generally against the percolation or passage of water to extreme depths will apply equally to this hypothesis also.

The theory of volcanic action which has of late years been most

* The general views expressed in this paper were laid before the Geological Section of the British Association at the York Meeting in 1881. See Report of Section C, p. 610.

generally accepted is that of Mr. Poulett-Scrope. As formulated by him in the successive editions of his standard work on "Volcanos,"* "the main agent in all these stupendous phenomena—the power that breaks up the solid strata of the earth's surface, raises, through one of the fissures thus occasioned, a ponderous column of liquid mineral matter to the summit of a lofty mountain, and launches thence into the air, some thousand feet higher, with repeated explosions, jets of this matter and fragments of the rocks that obstruct its efforts—consists unquestionably in the expansive force of some elastic aëriform fluid struggling to escape from the interior of a subterranean body of lava, *i.e.*, of mineral matter in a state either of fusion, or at least of liquefaction at an intense temperature. This body of lava is evidently, at such times, in igneous *ebullition*."† He further explains that the rise of lava in a volcanic vent is occasioned "by the expansion of volumes of high pressure steam generated in the interior of a mass of liquefied and heated mineral matter within or beneath the eruptive orifice," so that the vapour reaches the external "surface in a state of extreme condensation and entangled in the liquid lava which rises with and escapes outwardly, just as any other thick or viscid matter exposed to heat from beneath in a narrow-mouthed vessel *boils up* and *over* the lips of that aperture."

I might have felt some doubt as to the exact meaning of this passage, especially as the author proceeds to remark, that "at what depth those volumes of vapour are generated may be a question," but as he goes on to observe, "that the tendency to vaporisation must everywhere occasion an extreme tension" or expansive force throughout the mass, "only restrained by the enormons weight and cohesion of the superincumbent rocks," I infer from this and from the general tenour of his remarks that the steam being the original motive power, exists in and at the base of the molten magma. He says, "If any doubt should suggest itself whether this fluid is actually generated within the lava, or only rises through it, having its origin in some other substance, or in some other manner beneath, it must be dispelled by the evidence afforded in the extremely vesicular or cellular structure of very many erupted lavas, not merely near the surface, but throughout their mass, showing that the aëriform fluid in these cases certainly developed itself interstitially in every part. And although such vesicles or cells appear at first sight to be wanting in other lavas, at least in the lower portions of the lava-current after its consolidation, the microscope invariably, or almost invariably, discovers them. In those exceptional cases, where the rock is to appearance perfectly compact, it is allowable to suppose that the vapour it once contained escaped in ascending bubbles, or by exudation through

* "Volcanos." By G. Poulett-Scrope. 2nd Edit. (1862), p. 30.

† *Ibid.*, pp. 39-40.

extremely minute pores, or was condensed by pressure and refrigeration previously to the solidification of the matter."*

It must also be borne in mind that for this hypothesis to have any value, the explosive material must extend throughout the mass of lava and act from its base upwards, just as much as it is necessary that the powder in the breech of the gun should be at the back of the shot. It should therefore extend to the volcanic foci, at whatever depth that might be, and be there occluded in the lava.

Professor Judd, in his excellent summary of Mr. Scrope's views, remarks that on this hypothesis volcanic outbursts are considered to be "due to the accumulation of steam at volcanic centres, and that the tension of this imprisoned gas eventually overcomes the repressing forces which tend to its manifestation," and that "in the expansive force of great masses of imprisoned vapour, we have a competent cause for the production of fissures through which volcanic outbursts take place."†

Mr. Scrope does not enter upon the question of the mode in which the water has become occluded in the fluid magma. Sir Charles Lyell, however, in supporting the views of Mr. Scrope, says, "We may suppose that large subterranean cavities exist at the depth of some miles below the surface of the earth in which melted lava accumulates, and when water containing the usual mixture of air penetrates into these, the steam thus generated may press upon the lava and force it up the duct of a volcano, in the same manner as a column of water is driven up the pipe of a geyser."‡

Briefly the opinion of Mr. Scrope upon the cause of volcanic action is that it is to be attributed to the escape of high pressure steam generated in the interior of the earth. Before proceeding to discuss this hypothesis more fully, and to state my objections to the views of this distinguished volcanologist, I must refer to the remarkable paper of the late Mr. R. Mallet, in which the same subject is treated from an entirely different point of view.

According to Mr. Mallet, volcanic energy, as we see it on the globe, is *not the direct* product of primordial heat of fusion, although it is evidently due to the loss of that heat, and is the result of the cooling of our globe. He defines it thus: "The heat from which terrestrial volcanic energy is at present derived is produced locally within the solid shell of our globe by transformation of the mechanical work of compression or of crushing of portions of that shell, which compressions and crushings are themselves produced by the more rapid contraction, by cooling, of the hotter material of the nucleus beneath that shell, and the consequent more or less free descent of the shell by

* *Op. cit.*, pp. 36–7.

† Judd's "Volcanoes," pp. 33 and 189.

‡ "Principles of Geology," 10th Edit., vol. ii, p. 221.

gravitation, the vertical work of which is resolved into tangential pressures and motion within the thickness of the shell."*

The crushing of the earth's solid crust along lines of greatest weakness, is in this manner considered by Mr. Mallet to evolve heat sufficient to fuse portions of the crust and to cause the extrusion of the fused masses. He says, "The result of the crushing is to produce irregular masses, on the whole tending to verticality, of pulverised rock, heated more or less highly, that may extend to any depth within the solid crust; but it is only to such depths as water can percolate or infiltrate by capillarity that the deepest focus of volcanic activity can be found."

Geologists find many objections to Mr. Mallet's ingenious hypothesis. Amongst the most serious, and it seems to me fatal objections, are—(1) that it fails to explain the centralisation of the heat, for even if fully developed by sudden and paroxysmal movements, it would, unless confined to a very narrow line, which is not probable, be dispersed and dissipated throughout the whole mass affected by the pressure; (2) that there is an absence of volcanoes in the majority of mountain ranges where the pressure and crushing have been of the most powerful character; (3) while, on the contrary, in many volcanic areas there is little or no evidence of great lateral pressure, or of much disturbance of the strata beyond faulting.

The great mountain ranges of the Alps and Pyrenees, where the strata are tilted, contorted, and enormously crushed, do not contain a single volcano; the strata are highly metamorphosed, yet show no traces of igneous fusion. In the Andes, the volcanoes are mostly situated on flanking ridges, or on the lower grounds at their base, and rarely on the high central ridges. Volcanoes, in fact, are as often, or more often, on lines of fault than on anticlinal ridges. But lines of fault, even those of the greatest magnitude, show no fused walls, though the formation of slickenside surfaces must, seeing the great friction, have been attended with considerable heat.

I however entirely agree with Mr. Mallet in two of his propositions, namely, that volcanic action "is only one phase of a unique force which has always been in action . . . . since our planet was nebulous;" and in one sense "that without water we can have no volcano."†

§ 2. *Objections to Steam as the Primary Cause of Volcanic Eruptions.*

The chief objections to the hypothesis that the vapour of water is the primary agent in volcanic action, are—

1. The difficulties in the way of accounting for the presence of water in the deep-seated volcanic foci.

* "Phil. Trans.," vol. 163, p. 167.

† *Op. cit.*, p. 216.

2. The insufficiency of the elevatory force.
3. The want of agreement in *time and proportion* between the discharge of steam and the discharge of lava.

On the hypothesis of Mr. Poulett-Scrope it has to be assumed either that the water formed part of the original molten magma, or that the surface-waters find a passage by percolation or by fissures through the crust of the earth to the molten mass beneath. That water does penetrate to great depths, there can be no doubt, and if nothing interfered to check its descent, the extent and range of the percolation could hardly be limited. But various stratigraphical causes interfere with this transmission, such as the thinning out of the strata, faults, and uncomformity of superposition. These causes especially impede the flow of water in the more frequently disturbed Palæozoic strata, but in the less disturbed newer strata it is comparatively little affected by them. At the greatest depths in Tertiary and Secondary strata water is always, or almost always, met with in the permeable beds. It is otherwise with the Palæozoic strata generally; where, for example, as is so common in Coal Mines, the faulting of the measures divides them into separate segments or compartments, in each of which the supply of water from adjacent areas is cut off, and no fresh supplies being received from the surface, there is no further accession of water. Again, where Tertiary or Secondary strata overlie uncomformably Palæozoic strata, the interstices on the surface of the older rocks are so effectually plugged by the basement bed of the superimposed strata, that they are often rendered perfectly watertight. There is a remarkable instance of this in the coal-field of Mons,* where the Coal-measures are in places worked under a depth of 600 to 900 feet of loose sandy Cretaceous strata full of water, and yet are found to be perfectly dry, owing to the circumstance that the basement bed of the overlying strata has formed a sort of puddle cover, sealing up, as it were, the edges of the underlying strata. The percolation of the surface-water to great depths is, in consequence of these interruptions, far from being so general as might be supposed.

Admitting, however, the possibility of water descending in certain cases,—as through the fissures and crevices of crystalline rocks, or, in the absence of any mechanical conditions to stop its descent, through permeable strata,—it is a question whether its descent would not be stayed by the increase of heat at great depths, although under the enormous pressure it may remain liquid at high temperatures.

It is known experimentally that the pressure of steam which at 212° F. equals one atmosphere, is, at a temperature of 432° F., equal to that of nearly 24 atmospheres; and also that the rate increases with the rise of temperature, and faster at high than at low temperatures, as the following reduction from Regnault's tables shows:—

* The author in "Proc. Inst. Civil Engineers," vol. xxxvii, p. 129.

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Temperature.	Pressure of mercury.	Pressure in atmospheres.	Temperature.	Pressure of mercury.	Pressure in atmospheres.
F.	inches.		F.	inches.	
212°	29·89	1·0	332°	216·21	7·21
222	36·35	1·21	342	247·38	8·25
232	43·91	1·47	352	281·99	9·40
242	52·72	1·75	362	320·28	10·68
252	62·92	2·10	372	362·50	12·08
262	74·69	2·50	382	408·92	13·63
272	88·18	2·94	392	459·80	15·33
282	103·58	3·45	402	515·41	17·18
292	121·08	4·04	412	576·02	19·20
302	140·88	4·70	422	641·90	21·40
312	163·18	5·44	432	713·32	23·88
322	188·22	6·27			

Thus, while an increase of 50° F. to the temperature of water vapour at 212° causes an increase of pressure of only $1\frac{1}{2}$ atmospheres, the addition of another 50° gives an additional pressure of nearly 3 atmospheres; of another 50° gives 5 atmospheres; while 50° more gives a further increase of $8\frac{1}{2}$ atmospheres.

This rate of increase of pressure is nearly proportionate to the 5th power of the excess of temperature above −40° F. Pouillet employed empirical formulæ to ascertain the probable pressure at higher temperatures up to 516° C. These, although not mathematically exact, are sufficiently so for our purpose—at all events up to the temperature of 773° F., the critical point of water, at which new conditions would be involved.

Temperature.	Pressure in atmospheres.
510° F.	50 atmospheres
592	100 ,,
686	200 ,,
747	300 ,,
794	400 ,,
832	500 ,,
864	600 ,,
893	700 ,,
918	800 ,,
942	900 ,,
962	1000 ,,

At the critical point of water the pressure would be nearly 350 atmospheres, or if the rule holds to the temperature at which water may undergo dissociation, we should have a pressure exceeding 1000 atmospheres. In any case these conditions point to a possible term

at which the expansive force of vapour will exceed that of the hydrostatic pressure (especially modified as it is by friction) and the descent of the surface-waters is in all probability stayed.*

Adopting the conclusion arrived in the paper I recently laid before the Society—viz., of a mean thermometric gradient of 48 feet of depth per 1° F., the following will be the relation between depth and temperature down to a depth of 150,000 feet or 28½ miles, starting with an annual mean surface temperature of 50° Fahr.

Table of Temperatures at Depths taking the Thermometric Gradient at 48 feet per 1° Fahr.

Depth.		Temperature.	
Surface	=	50° Fahr.	
500 feet	=	60½	
1,000 ,,	=	71	
1,500 ,,	=	81	
2,000 ,,	=	92	
3,000 ,,	=	112	
4,000 ,,	=	133	
5,000 ,,	=	154	
7,776 ,,	=	*212*	*Boiling point.*
10,000 ,,	=	258	
15,000 ,,	=	362	
20,000 ,,	=	467	
30,000 ,,	=	625	
34,704 ,,	=	*773*	*Critical point.*
40,000 ,,	=	883	
50,000 ,,	=	1092	
100,000 ,,	=	2133	
150,000 ,,	=	3175	

If there are experimental errors, as I consider not improbable, such as would reduce the gradient to 45 feet per degree, the temperature at the depth of 150,000 feet would be 3383°, unless the increase of heat modifies the conductivity of the rocks at depths. Or if in centres of crystalline rocks and slates, as in Cornwall, and with a gradient of 40 feet, a temperature of 3000° might be reached at a depth of 120,000 feet or about 23 miles.

* M. Delesse, in his paper on the water in the interior of the Earth, considered that notwithstanding that water tends to pass into vapour at the high temperature of great depths, the pressure of the overlying strata and the resistance they offer to its return being greater than its tension, would cause it to retain its liquid state. But at a depth which he estimates at about 60,000 feet, and at a temperature of about 1100° F., the overlying pressure (taken at the rock weight), and the elastic force of the vapour of water would be in equilibrium. "Bull. Soc. Géol. de France," 2nd Ser., vol. xix (1861), p. 64.

Besides these, there are other considerations which should not be overlooked, although it is impossible at present to assign a value to them. Still they may be placed to a suspense account. The first is whether there may not be areas of certain rocks in which the gradient is more rapid than in other areas; and whether in tropical regions there is not generally a more rapid thermometric gradient. In the paper on Underground Temperatures, a few of the observations raise these questions, as questions for further inquiry.

The second point, which I have already mooted,* is more purely hypothetical. It is whether the effect of the excessive cold of the glacial period—or cold prolonged during so many thousands of years—may not possibly have left its mark on that portion of the earth covered for so long a period by perpetual snow and ice,—whether the loss of heat in the upper layers of the crust may not only have altered the thermometric gradient, but also induced, as it were, premature contraction by an excessive abstraction of heat during that period. Whether also that outer portion of the crust so affected might not now present a slower gradient than the present mean surface temperature would warrant, while at greater depths a normal more rapid gradient may still prevail. And whether or not this might possibly be an element in the present effective rigidity of the crust?

Taking therefore into consideration all the conditions to which water becomes subject with increasing depth and the rapid increase of temperature, together with the circumstance that while the pressure of water increases with depth in simple arithmetical progression, that of the elastic vapour of water is one of a very rapid geometrical progression, it becomes extremely improbable that water can penetrate beyond a certain depth beneath the surface. Roughly, it is a question whether 7 to 8 miles would not be a limit. At all events I feel it impossible to accept any hypothesis based upon an assumed percolation to unlimited depths, and am forced to look to other causes in explanation of the presence of water in volcanic eruptions.

It is true that the experiments of Daubrée, which will be further alluded to, show that owing to the force of capillarity, water can pass through porous strata against a considerable resisting pressure, but on the other hand Wolff's experiments show that the effects of capillarity decrease with the increase of temperature, and tend to prove that there is a point at which they would altogether cease.

It may also be a question whether at the high temperature at great depths, the vapour of water would not undergo decomposition, for M. H. St. Claire Deville† has shown that under certain conditions, at a temperature of from 1103° to 1300° C., it is dissociated into its

* "Phil. Trans.," vol. 164, p. 305.

† "Sur le phénomène de la dissociation de l'Eau," "Comptes rendus," vol. lvi, p. 195.

× 1760 × 3 = 8 × 5280 = 42240 feet = 8 miles

elements, and in so dissociating it augments its volume by one half, and its pressure in proportion.* That water is decomposed in contact with lava during eruptions, is rendered probable by the observations of M. Fouqué during the last great eruption of Santorin, for he found that the gases given off under water during the eruption, and collected as they ascended through the sea, often contained as much as 30 per cent. of free hydrogen, and from the circumstance that he also found free oxygen occasionally present, he considered it likely that the vapour of water exists in a state of dissociation in the lava during eruptions.†

Other geologists have contended for the possibility of water gaining access to the volcanic foci by fissures opening into the sea-bed.‡ These fissures are supposed to be formed by the molten matter struggling to escape. To this it has been rightly objected, that in such a case the lava would at once fill the fissure to the exclusion of the water. By others it has been suggested that the fissures are caused by the escape of imprisoned elastic vapours; but as Mr. Scrope remarks, this is reasoning in a circle, for while it supposes the aqueous vapour to be the cause of the disturbance, it yet proposes to introduce the water *after* the effects attributed to it had been produced.

The second objection is, that supposing it were possible for water to penetrate to the molten magma and to be converted into high pressure steam, would it be possible for it to force forward and gradually erupt a column of lava extending from the molten mass below to the volcanic summit? Bischof's§ hypothesis was founded on an erroneous estimate of the elastic force of steam.

Would not also, on the fissure hypothesis, the pent up elastic vapours, which are supposed to force the lava up the volcanic duct, necessarily take the line of least resistance, drive back the column of water in the fissure and escape with it?

But the objection to which I attach most weight and importance is one which deals with facts which are within the scope of actual observation. On the hypothesis that attributes the extrusion of lava to "the expansive force of some elastic aeriform fluid, struggling to escape from the interior of a subterranean body of lava," it would follow that no lava could escape without the accompaniment of the propelling aeriform fluid, nor could any large evolution of vapour or gases take place without a large eruption of lava, for the relative

* At the same time it is to be observed, that enclosed in a platinum tube water does not decompose at a temperature near the fusing point of the platinum.

† "Santorin et ses Éruptions," p. 232.

‡ "Bull. Géol. Soc. de France," vol. xiii, p. 178; vol. xvi, p. 43; and 2nd Ser., vol. i, p. 23.

§ "Edin. New Phil. Jour.," vol. xxvi (1839), p. 132.

discharge of steam and lava could not fail to bear some proportion one to the other.

Although the phenomena accompanying volcanic eruptions are so constantly recorded, those which bear in particular on this question are generally so mixed up with the other details, that it is not always possible to determine their relative bearing and sequence. There are, however, an ample number of cases to show that the discharge of lava is not in proportion to the discharge of steam, nor is the discharge of steam always in accordance with the escape of lava, which they should be if the hypothesis were correct. These conditions would seem on the contrary to be perfectly independent one of the other. It is of course conceivable that lava of an extreme fluidity and offering less resistance to the escape of the elastic vapours, might be ejected in lesser quantity than a more viscid lava, which presented more resistance, or that paroxysmal explosions may disperse the lava in aerial discharges, and reduce the importance of the quieter outflow; but these occasional occurrences would not affect the more general results. There are too many great eruptions that have been attended with a small discharge of lava, and too many of the largest lava streams have been erupted quietly and with a very small exhibition of explosive violence, to allow of much doubt on the subject. Sometimes, when the discharge of lava has been at its maximum, the explosive violence has been at its minimum, and, on the other hand, violent detonations have been attended with small overflows of lava.

According to Daubeny,* there is no recorded lava-flow accompanying the eruptions of Vesuvius prior to the eruption of A.D. 1036. This, however, may be the mere absence of record. Still, it would seem to point to the prevalence of paroxysmal eruptions like that of the great eruption of 79 B.C.

Mr. Scrope divides volcanic outbreaks into periods of moderate activity and of paroxysmal violence,† and he himself remarks that "the volume of lava poured out by an eruption does not preserve any constant proportion to the force or continuance of its explosions." He instances Etna‡ as an example of almost continual moderate activity with occasionally more or less paroxysmal outbursts. The volcano of the Island of Bourbon offers another example of the same kind. He further points out§ that "in all cases where lava is emitted its protrusion marks the crisis of the eruption, which usually attains the maximum of its violence a day or two after its commencement. The stoppage of the lava in the same manner indicates the termination of the crisis, but not of the eruption, for the gaseous explosions

* "Description of Volcanos," 2nd Edit., 1848, p. 225.

† "Volcanos," 2nd Edit., p. 16—19.

‡ *Ibid.*, p. 24.

§ *Op. cit.*, p. 23.

continue often for some time with immense and scarcely diminished energy." Vesuvius "has often continued in eruption for periods of several months, discharging moderate jets of scoriæ, lapilli, and sand, from temporary orifices at the summit or flank of the cone, or at the bottom of its crater, *when there was a crater;* while streams of lava welled out, *sometimes almost with the tranquillity of a water-spring* from the same or from contiguous openings."*

Professor Palmieri† says of Vesuvius, that on some occasions the eruptions commence with explosions and detonations of greater or lesser violence, ending with a great eruption and a copious flow of lava; and that at other times great eruptions have taken place without any precursory signs.

Professor Phillips observes of the great eruption of Vesuvius of 1794, which was characterised by the flow of some of the largest lava currents ever erupted from this mountain, that "for nearly a month after the eruption (of lava), vast quantities of fine white ashes mixed with volumes of steam were thrown out from the crater."‡

M. Ch. St. Claire Deville§ states that the great eruption of Vesuvius in 1855 was *one of the most tranquil.* The projections only lasted a few days, and the detonations soon ceased. The lava continued to flow for twenty-eight days, and formed the largest current which has passed out in the north-west direction.|| This eruption was in great contrast with that of 1850, which was one of the most violent and paroxysmal, when the mountain was changed in form, the central cone reduced, and the crater enlarged to 2 miles in circumference, *yet the flow of lava was comparatively small.*

The eruption of Etna of 1852 was one of unusual magnitude, and the flow of lava greater than ever witnessed, except probably in 1669. It commenced in August with violent explosions and ejection of scoriæ. The lava then began to flow from several openings, and flooded the country for a length of 6 miles and a breadth, in places, of 2 miles. The ejections of scoriæ continued during sixteen days, but *after that time they almost ceased*, except in a few smaller craters, though dense volumes of steam were occasionally discharged from the central crater, *but the flow of lava continued with little interruption through September, October, November, and December, and did not entirely cease until May,* 1853.¶

An eruption, which seems of itself almost sufficient to prove the

* *Op. cit.*, p. 17. The italics here and in the following pages of this chapter are mine.—J. P.

† "Eruption of Vesuvius of 1871–2." Mallet's Translation, pp. 94, 99–100.

‡ "Vesuvius," pp. 92–4.

§ "Bull. Soc. Géol. de France," 2nd Ser., vol. xii, p. 1065.

|| "Vesuvius," p. 107.

¶ Lyell, "Phil. Trans.," vol. 148, p. 18.

independence of the causes leading to the outflow of lava, and those generating the elastic vapours, is that of Santorin in 1866, recorded by M. Fouqué.* In the centre of the bay formed by the great encircling old crater-walls of the islands of Thera and Asprosini, stands the small island of Kaimeni, the product of later eruptions. On the 26th January, 1866, the loose blocks on the southern slope of this island began to move—on the 27th slight shocks were felt, gases evolved, and fissures rent in adjacent buildings. The ground in a small sandy bay was observed to rise, and by the 4th February the erupted mass consisting of blocks of lava, had attained a height of 32 feet. By the 5th, this protuberant mass of lava had increased to 230 feet in length by 98 feet in width, and 65 feet in height, and on the 7th to $492' \times 197' \times 98'$. The adjacent water was hot and the surface of the lava was consolidated, though it was incandescent at night. Until the 12th February there were no detonations and no explosion, notwithstanding the large quantity of lava emitted, for it was not confined to the matter above water, but it was, in places, gradually filling up the bay itself; and where there previously had been soundings of 103 fathoms, the depth was now reduced to from 40 to 70 fathoms.†

M. Fouqué remarks,‡ that "at the beginning of the eruption the discharge of lava was the most salient phenomenon; *the rock-emission proceeded in silence;* it was only at the end of several days that the explosions and ejections commenced and a crater formed (the volcano of Giorgios)." The explosions attained great violence on the 20th and 22nd, and on the latter day the column of vapour and ashes rose to a height of about 7000 feet. In April and May lava flowed more freely. The eruption was prolonged to 1869, when *the explosions were still frequent but the discharge of lava very small.*

Another eruption commenced in February 1867, in the sea-bed west of Kaimeni, and by the 17th an island (Aphroessa) was formed 328 feet long by 196 feet wide and 32 feet high; while the adjacent sea-bed was in places reduced from a depth of 296 fathoms to 108 fathoms. This also was effected *quietly and without noise*, and it was not until later that the explosions began.

So noiseless and so steadily continuous was the protrusion of these masses of lava at first, that Dr. Cigalli, who watched them from day to day, compared their growth to the steady and uninterrupted growth of a soap bubble.

Much of the lava of this great eruption was very compact, and not at all scoriaceous.§

* "Santorin et ses Éruptions," Paris, 1879.

† *Ibid.*, p. 36 *et seq.*

‡ *Ibid.*, p. xv.

§ *Op. cit.*, p. 72.

But probably the eruption most remarkable for its magnitude, and at the same time for its quiet, was that of Mauna Loa in 1855. In speaking of this eruption Dana says that there *was no earthquake, no internal thunderings, no premonitions at the base of the mountain.* A small glowing point was seen at a height of 12,000 feet, which gradually expanded, throwing off coruscations of light. A vent or fissure then formed, from which a vast body of liquid lava *rapidly but quietly flowed during several weeks* (a later account says 10 months), forming a stream of lava which extended a distance of 65 miles, with a breadth of from 3 to 10 miles. He adds that those eruptions of fiery cinders which mark so strikingly Vesuvius, are almost wanting about the craters and eruptions of Mauna Loa, and the few that there are, are mainly in connexion with the lateral cones.

On the other hand, Mr. Scrope remarks that the great paroxysmal eruptions of volcanoes are preceded by earthquakes more or less violent, frequent, and prolonged, "and begin generally with one tremendous burst, which appears to shake the mountain from its foundations. Explosions of aeriform fluids, each producing a low detonation and gradually increasing in violence, succeed one another with great rapidity from the orifice of eruption, which is in most instances the central vent or crater of the mountain." As a consequence of such eruptions, the cone is frequently found truncated, "the upper part having been blown off, and in its place a vast chasm formed, of a caldron-like appearance, and of a size proportioned to the violence of the eruption and its duration.*

One of the most violent of the explosive eruptions was that of the Cosequina in 1835.† This volcano is situated on a promontory south of the Bay of Formosa in Central America. The detonations were so violent that they were heard at a distance of 280 miles. So enormous was the quantity of ashes and scoriæ shot out of the crater, that for a distance of 25 miles they covered the ground to a depth of about 15 feet, and the finer dust was carried by the wind as far as Jamaica, a distance of 800 miles. It is not recorded that this great outbreak was accompanied by any lava-flow.‡ The mountain itself is only 480 feet above the sea-level.

From time to time the violence of other paroxysmal eruptions has blown off and truncated the cone of the volcanoes, and enlarged the craters, from the small dimensions they have when the eruption issues at the finished apex, to gulfs sometimes several miles in circumference and of great depth, eviscerating, as it were, the very centre of the

* "Volcanos," 2nd Edit., pp. 20–21.

† The great eruption of Krakatoa has taken place since this was written. It was one of the same character; we wait the report now preparing by a Committee of the Royal Society.

‡ Reclus, "La Terre," p. 668.

mountain. Scrope* mentions as examples of such paroxysmal eruptions,—13 eruptions of Vesuvius, 8 of Etna, 2 of Teneriffe, 1 of San Georgis in the Azores, 3 of Palma, and 1 of Lancerote (Canary Islands), and all the recorded eruptions of Iceland.

" Sometimes in these eruptions no absolute escape of lava takes place, scoriæ alone being projected. In all cases when lava is emitted its protrusion marks the crisis of the eruption, which usually attains a maximum of its violence a day or two after its commencement. *The stopping of the lava* in the same manner indicates the termination of the crisis, but not of the eruption, *for the gaseous explosions continue often for some time with immense and scarcely diminished energy.*"†

It seems to me therefore evident from these and such other cases, that there is no definite relation between the quantity of explosive gases and vapours and the quantity of lava discharged from the volcanic foci. It is conceivable that the enormous force of some of the explosions may, in the paroxysmal outbursts, shatter and blow to fragments all the lava as it rises in the crater, but this seems hardly sufficient to account for the proportionally large quantity which should accompany such vast volumes of vapours, were those vapours the cause of the extrusion of the lava. It is still more difficult to conceive on this hypothesis the excessive discharge of lava in tranquil eruptions without a greater escape of vapour.

If the escape of lava depended altogether on the escape of the imprisoned vapours, it is not easy to see how the constant supply, whether of the lava or of the steam, is maintained. The rise and escape outwardly of the lava in a volcanic vent has been likened to the boiling up and over of any other thick and viscid matter exposed to heat from beneath in a narrow-mouthed vessel,‡ and Constant Prevost compared it to the overflow caused during fermentation by the evolution of carbonic acid gas. But the cases are not analogous. In the one the aeriform fluid is part of the substance of the vaporisable matter, which is not the case with the lava where the substance causing ejection is foreign to it. In the first case the elastic fluids are generated by a molecular change of the heated substance itself, and the supply is therefore, so long as that lasts, unlimited; whereas in the case of lava, which cannot undergo such changes, it is only the supposed occluded vapour in it, that, with the relief of pressure would be subject to expand and escape, and thereby displace and expel a proportionate quantity of the lava. Besides, could that result take place before the lava began to rise? If not, there must be an independent cause to originate the rise. We might also ask whether that very rise of

* " Volcanos," p. 25.

† *Ibid.*, p. 23.

‡ Scrope's " Volcanos," p. 40, and Lyell's " Principles," vol. ii, p. 221.

the lava in the duct would not on the contrary increase the pressure in the volcanic foci in which the occluded vapour is present?

We have already pointed out the difficulty of accounting for the introduction of water into the volcanic foci. Even supposing it to be introduced and to cause a boiling over, that ebullition would go on so long as any of the imprisoned vapour remained in the lava; but when the expulsion of one or the other was effected, then the introduction of fresh materials from the outside, as in the case of the water in the Geyser pipes, would become necessary, or the boiling over of the lava would cease for want of supplies. If the water were present in combination with the lava in the volcanic foci, there is no reason why the passage to the exterior once formed, the eruption should cease until all the mass susceptible of boiling over should be expelled, in which case each eruption would be of longer or shorter duration, and a volcano would become extinct after one eruption. If, on the other hand, the expulsion were due to the access of water from the exterior, whether by fissures or by permeation, it is difficult to imagine such an influx of water without the previous action of some disturbing cause whereby the existing equilibrium under which the descent of the water is stayed, would be destroyed.

The only logical hypothesis on which I can conceive the vapour of water of gases to be present in the fluid magma of the volcano is the one suggested by Dr. Sterry Hunt, who considers that the magma is not part of the original molten anhydrous nucleus of the earth, but an intermediate layer derived from the first outer crust of old surface rocks which had been exposed to meteorological agencies, and retained, when fused under pressure, the water with which they had become permeated when on the surface. He supposes the original nucleus to have gradually become solid by pressure and loss of heat, and an outer crust to have formed. As that crust became thicker and covered by sedimentary strata accumulated upon it, its under surface, owing to the rise of the isothermal bars, was gradually remelted, forming an intermediate fluid layer between the solid nucleus and the solid outer crust.

Or else that of Mr. Fisher, who, from investigations in which he compares the existing inequalities of the earth's surface with such as could possibly have arisen from secular cooling, concluded that the interior of the earth had shrunk more than mere cooling alone would account for, and suggested that this was due to the presence of superheated water in large quantities in the original nucleus, and that the blowing off of this water during volcanic eruptions might have contributed materially to the diminution of the volume of the magma.* In a subsequent work† Mr. Fisher has applied this hypothesis more particularly

* "Trans. Cambridge Phil. Soc.," vol. xii, p. 414.

† "Physics of the Earth's Crust," chap. xv, p. 185 *et seq.*

to the explanation of volcanic action. He supposes a solid crust of about 25 miles thick resting on a fluid substratum of highly heated rocky matter in a state of igneo-aqueous fusion, and shows that if a crack were produced by any cause in the under surface of the crust it would become filled with the water substance or vapour given off from the fluid magma at a high tension. Whenever the rent, commencing below, opens upwards, vapour at a high tension will escape, and after a certain time will be followed by the magma itself, which will overflow at the surface because the water-substance expanding, owing to the diminished pressure, will render the whole column of less weight than an equal column of the crust. On this view he considers that any disruption in the crust which is sufficient to permit the passage of steam at an enormous pressure, would originate a volcano; and "much of the lava poured out might consist of the materials of the crust itself, fused by the passage of the gases through it, and so vary in its composition at different vents, and even at the same vent at different times."

I need not dwell on the other objections I feel to these hypotheses because the special one before-named applies equally to this,—namely, that, if they were true, all rocks formed under such conditions should exhibit evidence of the presence or of the escape of vapour. All volcanic matter should be more or less scoriaceous, whereas there are many lavas which are little, and others not at all scoriaceous; while the great sheets of basaltic rocks which have welled out from fissures at former geological periods, are likewise neither scoriaceous, except very superficially if at all, nor are they accompanied as a rule by *débris* indicating explosions and projections due to the presence of vapour and gases. Why also should not all rocks of igneous origin, as well as volcanic rocks proper, be scoriaceous, if such were the conditions of the molten magma beneath the solid crust? The general want of hydration in volcanic rocks and their associated minerals is likewise incompatible with such conditions.

It has been contended by some writers that large subterranean cavities may exist at depths in the earth's crust, and that the vapour of water under high pressure may be stored up in such underground cavities. But the pressure of the strata is so great at depths, that, as in deep coal pits, where no permanent cavities can be formed, owing to the "creeping" and falling in of the strata, it would be impossible for such cavities to exist in Sedimentary Strata, while in Igneous rocks the initial plasticity of the rock and pressure would effect the same object. Even if such cavities did exist, they could only be maintained by the action of an elastic fluid, whose pressure would exceed that of the superincumbent strata. Geology affords no evidence of such underground reservoirs, or of any having existed in former times. No great explosions of pent up steam show themselves during the disturbances, shocks and rents accompanying earthquake

movements, and no persistent issue of steam gives countenance to the supposition that the water permeates the rocks to great depths or exists there in natural cavities.

Natural cavities at depths in the earth's crust I hold to be impossible. There may be cavities in the Igneous rocks near the surface, due either to contraction, to rapid cooling without pressure, or to the shell left by the escaping lava streams. But these cannot take place at great depths. They are connected with subaerial action.

With regard to such cavities as those so common and of such extent in limestone rocks, it must be remembered that these cavities are entirely due to the descent of the surface waters to a definite level, and to their escape by the most readily available outlet, either in adjacent valleys, or at or near the tide line on the adjacent coast. Below that level there can be no active circulation of water, and no possibility, therefore, of great cavities, due to the passage of water through underground channels, being formed. Changes of level may have carried some of these superficial cavities to certain depths beneath the surface, but that they should have been carried to the great depths we are referring to, or be of any sufficient size, is more than problematical. In limestone strata they occur near the surface, or at a short distance beneath the surface; wherever these rocks have been worked at a depth beneath the line of water saturation, such cavities are of very rare occurrence. Deep mines reveal occasionally a few fissures, and some comparatively small cavities, but these are in mineral veins, which show no relation with active volcanic phenomena.

§ 3. *Influence of Volcanic Eruptions on Spring and Well Waters.*

It is a singular circumstance that although the presence of water in volcanic eruptions has been so long recognised, and the disturbances caused to wells and springs have been so often noticed, no systematic series of observations has been made either on the surface or on the underground waters in connexion therewith. There are many allusions and incidental notices, but nothing in the form of special and exact details. Most writers on the subject speak of the disturbances to wells and springs as a common or obvious fact; but a series of extended and accurate observations is much needed.* In the absence of more exact data, we have to avail ourselves of general observations made by witnesses on the spot, amongst whom are many competent authorities.

The great eruption of Vesuvius of 1813–14, which commenced with a few trifling explosions and shocks in September, and by a small eruption of lava in October and November, followed by the great

* The observations should not be limited to the volcanic area, but should extend to the sedimentary strata around, and to some distance from the centre of eruption.

eruption of December, was witnessed by M. Menard de la Groye,* who remarks that "towards the end of May the well-waters of Torre del Greco and Torre dell'Annunziata failed, and that this was an ordinary precursory symptom of the eruptions." In June the waters continued further to lower, and "in the first fortnight in July they fell so low as to alarm the population," while "in October the wells of Resina, Torre del Greco, and other places failed in a surprising manner."

Professor Phillips briefly records† the following instances:—"July, 1804. Severe earthquake—diminution of springs." In May, 1812, the wells failed or were much lowered at Torre del Greco and Resina, as well as a thermal spring. In June, July, and August, heavy rains occurred; yet this did not restore the water in the wells, which still remained low, and even lower than before in September, and this scarcity was felt along the whole Vesuvian coast, and in the valley of the Sarno. Early in 1822 the wells lost their water. August, 1833, water failed in the wells.‡ The loss of water has sometimes been attributed to other causes, such as the state of the rainfall, &c., but Professor Phillips specially observes that this sinking of the wells cannot be explained by reference to the previous state of the weather;§ and, after a careful examination into all the phenomena connected with the eruptions of Vesuvius, he alludes again to "the sinking of water in the wells around Vesuvius—the total drying up of some, and the increased descent of the bucket in all," during times of volcanic disturbances, as an important fact.

M. Ch. St. Claire Deville|| remarks: "It is well known that there is only one tolerably certain indication of an approaching eruption of Vesuvius, and that is the disappearance of the water in the wells of Resina and Torre del Greco."

According to Poulett-Scrope,¶ the threatening indications of an approaching crisis "are accompanied by the disturbance or total disappearance of springs, and such accidents as the cracking, splitting and heaving of the substructure of the mountain must naturally occasion."

Professor Guiscardi, of Naples, in answer to my inquiry, writes,** "As a rule, the water of wells in the neighbourhood of Vesuvius undergo changes in quantity, and even quite disappear before the commencement of eruptions. Only as well as I know in the eruption of 1861, the phenomena followed the eruption. I add a list of such diminishing and drying wells.

* "Journ. de Phys. et de Chim.," vol. lxxx, p. 390.

† "Vesuvius," p. 96 *et seq.*

‡ *Ibid.*, p. 140.

§ *Ibid.*, p. 141.

|| "Bull. Soc. Géol. de France," 2nd Ser., vol. xiv, p. 254 (1856).

¶ "Volcanos," 2nd Edit., 1862, p. 21.

** Letter to the author dated 1st Sept., 1881.

"1843. Decrease of water in the wells of Resina; it was preceded by emission of lava.

"1846. Some wells of Resina dried, and emission of lava followed.

"1846. Six adventive cones in the crater; water decreases at Resina in wells.

"1847. Decrease of water in the wells of Resina; great lava flowing.

"1848. Water decreases in the wells of Resina and Torre del Greco. Earthquakes in the neighbourhood of Vesuvius. Lava flowing.

"1849. The same decrease of water—strong explosions, bellowing, and lavas.

"1850. January 23rd, at Resina and Torre del Greco decrease of water in wells. Strong explosions. February 5, lava poured out with bellowing.

"Before the eruption of 1794, there was at Torre del Greco a small torrent, capable, it is said, of moving four mills. After the eruption the torrent got very poor, so that the water scarcely supplied a fountain. After the eruption of 1861, there was an increase of water in this fountain, and in some small springs near the shore, and one was noticed in the sea itself, which lasted nearly a month.

"There is a well on a farm of some relatives of mine, at St. Georgio di Cremano, in right line nearly 4 miles from Vesuvius, 150 feet deep, and plentifully fed by a spring. After the eruption of 1861, the water began to decrease, and a year after it was quite dry. This was followed by so abundant an emission of carbonic acid, that the well had to be stopped up."

I must observe, however, that the high authority of Professor Palmieri is against this view.* He states that previous to the eruption of Vesuvius in 1871–72, the water in the wells was neither deficient nor scarce, but was very acid afterwards. He elsewhere mentions that he considers these supposed premonitory signs either only to happen occasionally, or to be mere coincidences, such as the coincidence of a dry or rainy season. But the weight of evidence is certainly against this opinion, and, as I shall presently explain, there may be tracts that have an independent water-level which escape the surrounding disturbance, and it is not impossible that this very circumstance has led to the selection of such areas for the sites of towns and villages on the slopes of the mountain.

The more local springs which supply the shallow surface wells may remain undisturbed, while at other points the deeper-seated springs having a wider range may be tapped and drained. Again, the water in

* "The Eruption of Vesuvius of 1872," translated by R. Mallet, F.R.S., p. 135.

the superficial volcanic strata will usually flow towards the circumference of the mountain, in consequence of the beds by which they are held up dipping from the central crater; while the springs in the sedimentary strata lie in the continuous planes traversed by the volcanic duct, and towards which they may often dip. Some irregularity in the phenomena is therefore to be expected, and while in most places the wells suffer, it is quite intelligible that in others they may be but little affected.

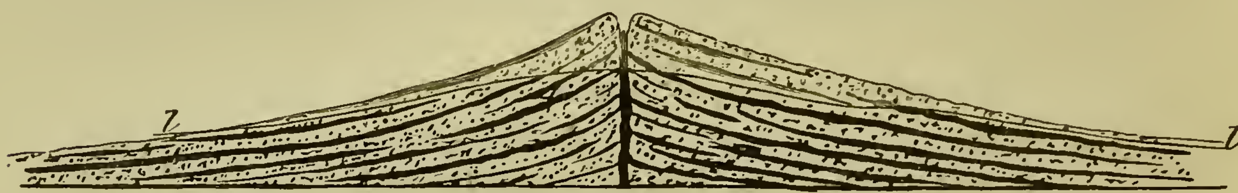


Fig. 1.—Diagram section of a volcano. The dark bands represent lava-streams; the dotted spaces, ashes and scoriæ; and the line *l*, the water level in the mountain.

As bearing upon the subject of the disturbances to which water-bearing strata are liable in volcanic districts, we have the evidence of M. Mauget, a well-engineer of great experience, respecting the sudden changes of water level in the Neapolitan area, during his residence there. There were eruptions of Vesuvius in 1865 and 1867, but none in 1866. Nor were there any important earthquakes, but a number of minor ones are recorded.

M. Mauget says that in May, 1866, the wells and springs around Naples began to be affected, and continued to diminish until June, but considers that this might be due to ordinary causes, such as lesser rainfall. On the 29th June a sudden change took place. The waters of the aqueduct, which brought in the water from a distance of 12 miles, and of the canal of Lagno di Mofita, as well as of various rivers, became troubled and reduced in a surprising manner. The next day the waters became bright, but were found to be reduced to the extent of one-fifth of their volume. The great springs of the Sannio district were reduced by one-third; and the town of Sorrento was deprived of all potable water. This water is brought in by an aqueduct from the neighbouring hills, which consist of Eocene or of Cretaceous strata. The whole district, from the foot of the Apennines to the Neapolitan coast, was affected over an area of 66 miles square.

At the same time various artesian wells in the valley of Sebito became sanded up and greatly reduced in their flow, and the two deep artesian wells of Naples threw up above 200 cubic mètres of trachytic and pumiceous sands and lapilli.*

It is evident that this diminution in the surface waters could only

* "Sur les variations subites dans le régime de divers cours d'eau dans l'Italie Méridionale," "Comptes rendus," vol. lxiv, p. 189 (1867).

have been caused by their absorption under ground, either to restore some water level reduced by a former eruption, or to fill fissures in course of formation preceding the eruptions of 1867 and 1868.

It seems to me, therefore, to use the words of Professor Phillips, that the observations respecting the effects produced on wells and springs by volcanic eruptions and earthquakes, "have been too often and too carefully made to allow of a serious doubt on the subject;" he asks, "What is the cause of it? and why is it an indication of coming disaster?"

§ 4. *The Hydro-geological and Statical Condition of the Underground Waters in and under a Volcanic Mountain.*

The cause is, I believe, not far to seek, when the hydro-geological conditions of the strata composed above of volcanic matter, and below of sedimentary strata, are considered.

So well known is the absorbent power of a volcanic surface, that the mention of the fact hardly seems necessary, except in corroboration of subsequent statements and for the purpose of independent testimony. On ordinary strata it is roughly estimated that about one-third of the rainfall passes under ground, but on volcanic surfaces the whole rainfall soon disappears, a small proportion only being lost by evaporation. Amongst innumerable notices of this fact, it will suffice to mention those of two experienced authorities. Lyell remarks on the dry and arid surfaces of Etna, and on the rapid absorption of the rainfall, and observes that "the volume of rain-water and melted snow commonly absorbed by a lofty mountain like Etna, is enormous;* again, Piazzi Smyth, in describing his ascent of Teneriffe, says, "that though so much rain had fallen lately, not a trickling stream, not even a drop of standing water, was anywhere to be seen; the pumice-stone ashes had swallowed all up." †

Volcanic mountains being composed of streams of lava of very variable width and length, irregularly alternating with more widely spread layers of scoriæ and ashes, the whole mass would be permeable were it not that the decomposition of some and the consolidation of other beds, by atmospheric and aqueous agencies, have formed here and there impermeable beds, which hold up the rain-waters, and furnish local supplies to wells and springs. But where such impermeable beds do not intervene, the rain-water penetrates to greater depths, and is there stored until the line of water-level reaches to such a height that the hydrostatic pressure forces it outwards, and causes it to escape at the points *l* as springs either temporary or perennial (fig. 1).

This storage may take place either in the lava or in the beds of scoriæ and ashes. Solid lava is impermeable, but water penetrates

* "Phil. Trans.," vol. 148 (1858), p. 763.

† "Teneriffe," p. 349.

through, and is held in, the numerous fissures and cavities by which it is traversed. These fissures are due to contraction on cooling, and to the fractured state of the lava produced by the splitting caused by subsequent disturbances, whilst larger cavities are produced by other causes. Of these, the two most important are—1st, the escape of vapours while the lava is consolidating. Sometimes the hardened outer crust of the lava is raised in great blisters, which, on the escape of the vapour, are sufficiently solid to retain their position, and remain like so many empty beehives on the surface of the lava streams. The Grotta delle Palombe, on Etna, which, according to Waltenhausen, has a length or depth of about 500 feet, and a height in places of from 70 to 80 feet, and the great ice cave near the top of the Peak of Teneriffe, described by Piazzi Smyth,* and so large as to contain a lake of water of considerable size, are attributed by them to the escape of elastic vapours.

2nd, the escape of lava from a lava stream after the exterior of it has become solid, when an empty shell in the form of a cave or tunnel is left. These tunnels or caverns are of common occurrence, and often of large size. Scrope observes† that "among the lavas of Etna, Bourbon, Iceland, St. Michael, Teneriffe, and many others, caverns of very large dimensions are thus formed beneath the surface of a lava stream, and often imitate in their extent and windings the well-known caves worn by water in limestone rocks." Phillips and others notice the occurrence of similar tunnels in the lavas of Vesuvius, but they are all small.

In the great volcanic mountains of South and Central America, Humboldt long ago inferred that large cavities filled with water must exist in consequence of the ejection of water, with small fishes and tufaceous mud, from fissures caused by the earthquake shocks which precede the eruptions of the volcanoes in the Andes.‡

A French geologist, M. Virlet d'Aoust, has, moreover, given particulars of two great tunnel-caverns of Central America,§ which will serve to indicate the magnitude of some of these subterranean reservoirs. The first is that known as the *Cueva de Chiuacamoté*, near Pérota, which he was assured extended several leagues in length (!) He found it to be a cavern of great size, and divided into compartments by falls of the roof. The floor is covered with a sandy gravel, and the side walls, here as in the cave of Custodio, exhibit grooved lines covered with slight calcareous incrustations indicative of old water-levels. The other is the *Breña de Custodio*, in the State of San-Luis Potosi, of which he says that it forms a perfect semispherical tunnel

* "Teneriffe," p. 352.

† "Volcanos," 2nd Edit., p. 79.

‡ "Cosmos," Sabine's Translation, vol. i, p. 230.

§ "Bull. Soc. Géol. de France," 2nd Ser., vol. xxiii, p. 34.

of the size of our largest railway tunnels, at its end dipping towards the centre of the mountain.

Cavities originating in these ways must have been formed at all times and in many lava streams, and although a certain number of them, especially those due to the upward escape of elastic vapours, may have been filled up by succeeding lava streams, this would not be the case with tunnel-caverns opening downwards. Nor would these streams always fill up even open fissures, as they push before them a mass of solidified *débris*, which forms a pavement protecting the underlying mass.

The lava throughout a volcanic mountain may therefore contain a greater or lesser number of caverns, which serve, whenever they happen to lie below the normal line of water-level, as so many reservoirs. The mass of the lava is further riddled with fissures of all dimensions, which act as water-channels and channels of intercommunication.

Again, the beds of scoriæ, ashes, and tufaceous deposits serving to build up volcanic mountains, and which overlap the lava streams, and extend to considerable depths, are often water-bearing. Some contain powerful springs, like stratum No. 4, which was met with in the Palace well at a depth of 368 feet beneath the surface at Naples (p. 141). The shallow surface wells of the district are commonly in beds of this character.

Even the more impermeable tufaceous beds contain cavities which when under the line of water-level, must serve as reservoirs. These cavities, which attain a size of 2 feet or more in height, and are lengthened out in a vertical direction, like the flues of chimneys, have been formed by the disengagement of elastic vapours during the consolidation of the beds, that consist, in the Naples district, of volcanic tuff with trachytic and other rock pebbles.* These beds have a wider extension than the lava masses, which further decrease in importance as they trend from the central area of eruption.†

The dykes running in vertical lines through volcanic mountains form another structural feature having an important bearing upon the question under consideration, for they traverse radially the beds of ashes, scoriæ, tufa, and lava wrapping round the central duct, with which they serve to place them in communication. Besides these great radial dykes, which are often extremely numerous, there is a network of small fissures or dykes branching off from them in all directions.

During the eruption of Etna in 1865, a rent was formed at the

* Dufrenoy, "Ann. des Mines," 3rd Ser., vol. xi, pp. 113, 120 (1837).

† Some volcanic mountains are, however, composed almost entirely of ash and scoriæ beds, and others of lava streams; the line of water-level will be modified in accordance with these conditions.

crater of Frumento, which extended in a direction away from the central cone for a distance of $1\frac{1}{2}$ mile. Scrope says that in nearly every lateral eruption of Etna, the production of such a fissure has been observed. Similar instances are not wanting in Vesuvius. In 1738 a fissure crossed the whole island of Lancerote; while in the great eruption of Hecla of 1783 the fissure which was then formed was supposed to extend not less than 100 miles in length.*

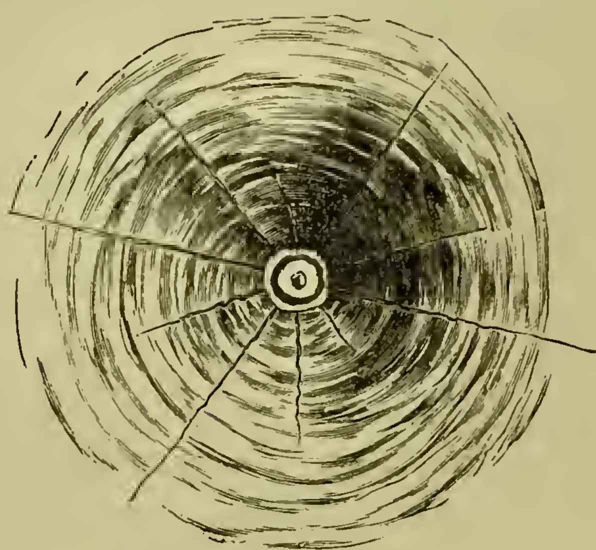


Fig. 2.—Diagram plan of a volcano, showing the radial lines of fissures or dykes.

Scrope further remarks that "the rents thus produced in the frame of a volcanic mountain are sometimes of such a size as to cleave its whole mass in two. This occurred in the volcano of Inachian, one of the Moluccas, in 1646. The crater of the Soufrière of Montserrat, and the volcanic cone of Guadaloupe both appear to have been thus split through. So also the Montagne Pélée of Martinique." Piazzi Smyth states that the cinder beds surrounding the summit of Teneriffe are traversed by dykes proceeding in radial lines from the Peak.† Phillips describes some of the dykes and fissures of Vesuvius, and gives a section showing the relative position of the ejected *débris* and lava beds of this mountain, and of the dykes radiating from the central core.‡

These dykes, like other masses of lava, have generally become fissured in cooling, and the interstices thus formed serve as water channels, not only for the rain which falls upon them, or to small springs high up the mountain as in Teneriffe,§ but, what is more important, they may serve as channels of drainage to the water-bearing scoriaceous and lava beds which they intersect. For it will be understood from the preceding account that these latter beds may often

* "Volcanos," 2nd Edit., 1862, pp. 161—163.

† "Teneriffe," p. 80.

‡ "Vesuvius," pp. 132 and 191, and Pl. VI.

"Teneriffe," p. 86.

form independent and isolated water-reservoirs; but, traversed as they are by dykes communicating with the central mass, these dykes serve as so many conduits to carry the water from the separate water-reservoirs and drain them into the central duct (fig. 2) whenever the normal hydrogeological conditions are disturbed. At such times the dykes therefore contribute greatly to the discharge of water into the interior of the volcano.

Very little is known of the substrata of a volcanic mountain. We know that Vesuvius, Etna, and Hecla stand on Tertiary strata—that some volcanoes in America stand on Cretaceous or Jurassic strata, and others probably on crystalline rocks, but of the stratigraphical details underground we have very scanty information. The only instances that I am acquainted with are the sections obtained in boring for the two artesian wells constructed in 1865–66 at Naples by MM. Degousée and Laurent, of Paris. These supply very important data not only respecting the volcanic beds, but also respecting the sedimentary strata beneath. One well is situated in the Piazza Villa-Reale, and was carried to a depth of 1106 feet, and the other, in the gardens of the Royal Palace at Naples, 72 feet above the sea-level, was carried to the depth of 1524 feet. The details given of this latter by M. Laurent are as follows:—*

Section of Artesian Well in the Palace Gardens, Naples.

		Thickness. mètres.	Depth. mètres.
Volcanic ejectamenta.	1. Soil and made ground	16·50	16·50
	2. Yellow volcanic tuff	52·50	69·00
	3. Green ,, ,, ...	33·00	102·00
	4. Volcanic ashes, in places argillaceous, and containing numerous pebbles of trachyte .... *1st spring*	103·40	205·40
	5. Greenish volcanic tuff	7·00	212·40
	6. Grey clay................	8·10	220·50
	7. Grey marly tuff with trachyte	4·00	224·50
Sub-Appenine strata.	8. Sandy marl with veins of lignite	25·00	249·50
	9. Grey marly and bituminous sands, with mica. *2nd spring*	27·00	276·50
	10. Hard sandstone	1·80	278·40
	11. Compact shelly marl	44·80	323·20
	12. Alternating micaceous sands, soft sandstones and carbonaceous marl.... *3rd spring*	48·70	371·90

* "Guide du Sondeur," 2nd Edit. 1861; vol. i, p. 137; ii, p. 496; and Pl. L.

		Thickness. mètres.	Depth. mètres.
Sub-Appenine Strata, *continued.*	13. Micaceous marl and siliceous limestone	7·81	379·70
	14. Compact micaceous marl ..	53·19	432·90
	15. Compact marl with layers of limestone	25·72	458·62
	16. Argillaceous limestone	2·00	460·62
Eocene.	17. Macigno (a hard calcareous sandstone) ...... *4th spring*	4·08	464·70

No ascending spring was met with until the volcanic ashes stratum No. 4 was reached at a depth of 368 feet. Another spring was found at a depth of 830 feet in the Tertiary marly sands No. 9; another in the micaceous sands No. 12 at 1106 feet, but no spring of the desired volume was met with until a sandy bed under the Macigno was reached at a depth of 1524 feet. The discharge of water from this bed amounted to nearly 2 cubic mètres per minute, and rose about 30 feet above the surface, so that the water could be used as a natural fountain in the Palace gardens. In the Piazza the artesian waters formed another natural fountain rising 8 feet above the surface.

These wells, therefore, show the existence of one important spring in a stratum of volcanic *débris*, and of three springs in the sedimentary strata beneath. But this only gives the more powerful ascending springs; bodies of water of lesser volume, or which do not rise to the surface, escape notice in works of this description.

The overflow of the water from the bed of volcanic ashes proves that the bed comes to the surface at a level higher than that of the ground where the well is situated, and as the water has sufficient ascensional force to rise several feet above the ground, it must necessarily, in order to overcome the resistance or friction of the bed through which it passes, stand at its outcrop in the central volcanic area considerably higher than at the point of overflow. There must, therefore, be a continuous sheet of underground water, the level of which rises towards the centre whence the water-bearing bed proceeds. In this way all the permeable beds of a volcanic mountain will be charged with water, the level of the water rising with the distance from the point of escape and with the height of the mountain. Everywhere beneath the level of saturation the surface-waters will eventually fill all fissures and interstices, and lodge in them permanently, unless disturbed or drawn off by artificial or natural means (see fig. 1).

This level depends, when there are alternating permeable and impermeable beds, on the height of outcrop of the former, and, when the whole mass is permeable, on the texture of the rock, or the friction to which the water is subjected. In the Chalk hills of the south of England which are composed of a comparatively homogeneous

rock, but variably fissured, the rise of the line of water-level varies from 13 to 150 feet in the mile, and in some strata it is even more.

It will therefore be apparent that in the case of the irregular and complex beds forming a volcanic mountain, the height of the water-level is subject to too many conditions to be determined accurately, except by experiment, and for this few opportunities present themselves. There is, however, an available natural datum line, namely, that furnished by the escape of springs, at certain high levels on the mountain slopes.

As springs issuing from a body of homogeneous strata or strata which intercommunicate, depend for their permanence upon the water stored up in the interior of the mountain, at a level above that of the point of escape, it follows that if there is a point of permanent escape, we may conclude that in the ground behind, all the strata below that level are under the line of permanent saturation, and therefore charged with water; and further, as just said, this line of permanent saturation must stand the higher the further it goes into the body of mountain.

Now, on Etna, Wattershausen* describes a spring in the valley of St. Giacomo, near Zafarana, which he says is the only point at so high a level at which a tolerably strong spring constantly issues. It at once forms a small waterfall, and runs some distance until lost in some volcanic sands lower down. The strata, where they issue, are composed of alternating layers of tuff and compact lava. Its escape is due to the circumstance that there is here a ravine which cuts through the bed, and either touching on the line of water-level or intersecting the junction between an impermeable and a permeable bed, and thus taps the subterranean waters. Wattershausen does not give the height of the ground, but from a section of Abich's, which passes near the spot, I infer it to be about 2000 feet above sea-level.† On the other side of Etna the river Simeto, or one of its tributaries, rises near Bronte, at a height of about 2200 feet above sea-level. This likewise indicates the existence of a perennial spring. I find also that at other points around the mountain at and about this level, streams commence which point to a like line of water-level.

These figures are only roughly approximate, but they constitute our only available data, and in taking a mean level of 2000 feet, I believe I am rather below than above the mark. If, therefore, we take Wattershausen's section of Etna, supplemented by Abich's, which follows nearly the same line, and gives, moreover, the height of the several points, the following diagram would represent generally the *massif* of the mountain and the position of the line of saturation.

From the points of permanent issue which we have noted at Zafa-

* "Atlas de l'Etna," Part I and Pl. V.

† Vesuvius and Etna, 1837. Sections of Etna.

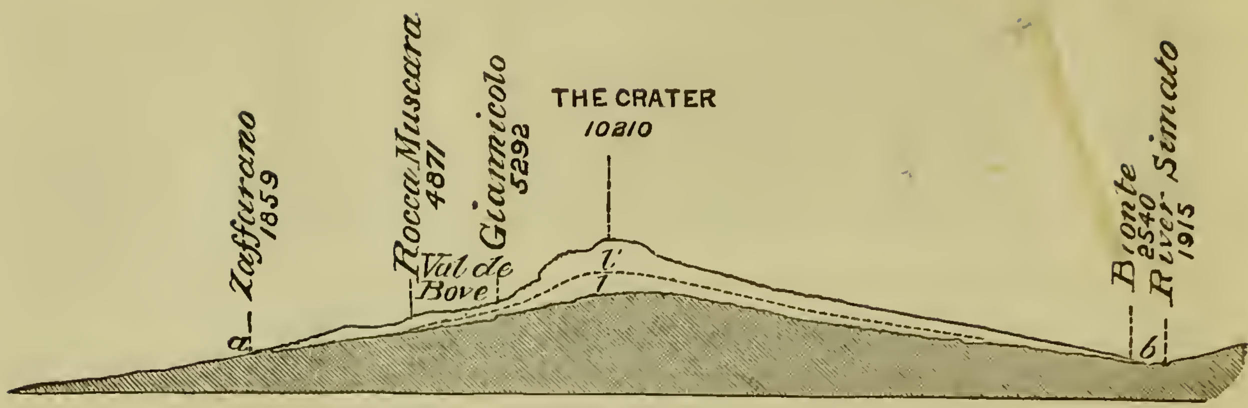


Fig. 3.—Diagram section of Etna.

rana and near Bronte, the line of water-level will rise in proportion as the ground rises between *a* and *b*; and in the same way in the great central dome which rises rapidly above the lower slopes, the water-line will rise more suddenly. It is therefore possible that in the centre of the mountain the line of permanent saturation, *l*, may occasionally stand higher, *l′*, than the top of the Val del Bove (5292 French ft., Abich). It may lie too deep for springs to issue, but the remarkable flood in that great depression described by Lyell,* and connected with the eruption of the year 1755, seems explicable on the supposition of a high central water-level more readily than on the assumption of the sudden melting of a mass of ice in the interior of the mountain. For although ice may be formed and retained under a covering of lava in the manner described by Lyell near the summit of Etna, the cold would not penetrate to a sufficient depth to allow of the accumulation of a mass of ice of the dimensions required for so great a flood. Any body of ice must be superficial, as the increase of heat with the depth from the surface would be a bar to its existence in the interior of the mountain, independently of the heat diffused at all times from the central duct. Nor would the sudden melting of the snow, which never lies very deep, and would frequently recur, explain the sudden great and exceptional outburst of flood-waters described by contemporary writers.†

On the other hand, heavy rains or the prolonged repose of the volcano, may have resulted in the exceptional rise to *l′* of the level of the underground water-line, *l*, so that if one of these radial fissures, so frequently formed during the eruptions of Etna, suddenly opened in a direction to traverse the water-logged strata, the effect would be to tap and drain at once the whole of this subterranean reservoir to the level of the point of escape—in the Val de Bove—a point still about 5000 feet below the summit of the mountain; while the water, coming as it would from the centre of the mountain, would also account for its reported heat.

* "Phil. Trans.," vol. 148 (1858), p. 68.

† Canon Recupero, who reported on the catastrophe, came to the conclusion that the water was vomited forth by the crater itself, and was driven out from some reservoir in the interior of Etna (Lyell, *op. cit.*).

This intersection of the line of water-level in Etna was probably due to the peculiar shape of the mountain, and the rapidity of the slopes above the Val del Bove. In volcanic mountains generally, this level is too depressed to be within reach of surface irregularities and fissures.

With respect to the condition of the sedimentary strata under a volcanic mountain, very few observations have been recorded, M. Constant Prevost, after visiting most of the volcanic districts in Europe, concluded that they were not in general much disturbed—that the volcanoes were on lines of fissures but not on lines showing much lateral compression, or on anticlinals. If we may take Vesuvius as a type, we should conclude that the sedimentary strata pass under the mountain and crop out in the adjacent sea-bed with little interference from faults. For the tertiary strata under Naples, come to the surface on the hill ranges further inland, and dip continuously seaward; and the fact of the overflow of water from the water-bearing beds—water of course passing down from the outcrop on the surface—to the height it actually attains, shows that the continuity of the beds cannot be materially interrupted.

The well-sections at Naples determine the existence of at least four water-bearing strata, of which the deeper one (1524 feet) discharged about 600,000 gallons daily, rising 102 feet above the sea-level. So great a pressure would show that this stratum had its outcrop inland at a considerable elevation above Naples, and the volume of the spring would prove that the head of underground water above the line of sea-level was large. Consequently, as the plane of this water-bearing bed must be traversed under Vesuvius by the volcanic duct, the sides of that duct or fissure will at that point be subject to the amount of hydrostatic pressure indicated by these conditions, or to a pressure, apart from friction, equal to that of about 53 atmospheres.

With respect to the ordinary mode of escape of the underground waters, that portion held in the more superficial volcanic beds will escape as springs on the slopes or at the foot of the mountain; but with respect to the underlying sedimentary strata—when they are adjacent to the sea and crop out in the bed of the sea—the surplus waters (or those annually added to the underground stores by the rainfall) will escape, 1st, in springs flowing on the surface; 2nd, by springs issuing in the sea-bed—and the size of these springs will depend on the hydrostatic pressure, and on the resistance and friction of the conducting strata. When the water-passages are contracted, as in sand and sandstone, the submarine springs will be small and slow: but when large and more open, as in limestones, the discharge in the sea-bed will, as on the coast of Spezzia and elsewhere on the Mediterranean, form large and powerful springs of fresh water rising through the waters of the sea.

Such are the hydro-geological conditions of a volcanic mountain in a state of rest. The effects when that equilibrium is destroyed will now be discussed.

§ 5. *Condition of the Underground Waters during an Eruption.*

So long as the volcano remains in a state of rest, so long will the hydro-geological conditions described in § 4 continue unchanged. The level, *l*, of the underground waters may rise; but, as in the meantime cooling has, by causing solidification, isolated the molten lava, no result is produced except that arising from the trickling of the surface-waters on the yet hot surfaces, giving rise to the small columns of steam common during the periods of rest. After a prolonged period of repose, even these minor effects cease. It may happen that if the crater is very deep and there has been a long interval since the last explosion, that the water-level may mount into the crater and give rise to a lake. In most cases, however, such lakes are due to the relatively low position of the crater with reference to a part of the adjacent ground, or to the decomposition of the lava, whereby it has become retentive of the rainfall. Such bodies of water are important in the event of any fresh eruption.

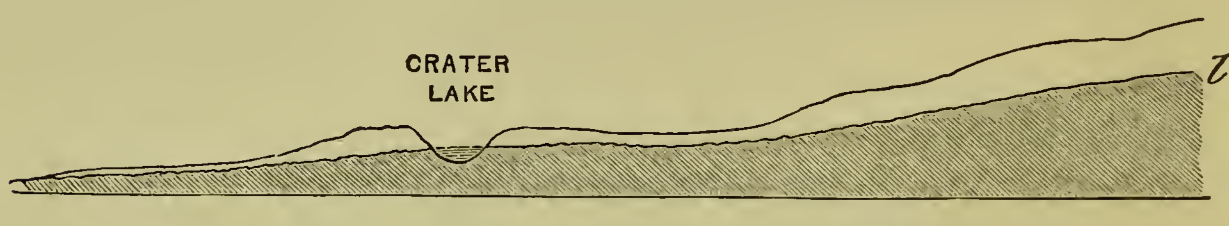


Fig. 4.—Crater Lake dependent on the general water-level (*l*).

Crater lakes are not so common or of so large a size in Europe as in Central America. The lake of Atitlas, 1558 mètres above the level of the Pacific, is 20 × 15 kilomètres large, and of a depth yet unascertained. The crater lake of Masaya in Nicaragua is 8 kilomètres across, and 150 mètres deep in the centre. In 1852 this lake suddenly appeared as though boiling, and a violent explosion shortly followed. The volcano of San Salvador is 2300 mètres high, and at the bottom of its crater, which is 700 to 800 mètres in diameter, and 400 to 500 mètres in depth, is a very deep lake. Another large crater lake, 12 kilomètres west of San Salvador, is level with the ground and 200 mètres deep.*

The crater lakes, however, are an exceptional feature. The great body of the rainfall becomes stored within the mountain itself, and makes itself visible only by springs on the lower slopes of the

* "Voyage Géologique dans la République de Guatemala et de Salvador," par MM. Dollfus et de Mont-Serrat, 1868, pp. 103, 106, 318-20, 374-5.

mountain. Its distribution must be irregular from the circumstance that volcanoes consist of alternating beds of permeable scoriaceous and of solid or decomposed impermeable materials, and as each of these is of limited extent, there may be a number of independent water-levels. It consequently follows that one may be affected by the disturbances accompanying an eruption, while others adjacent do not suffer, or suffer but little. It is only when these several levels are traversed by the same set of rents that intercommunication is established. The following section shows how numerous are the beds on the flanks of a volcano, and how they are traversed by dykes.

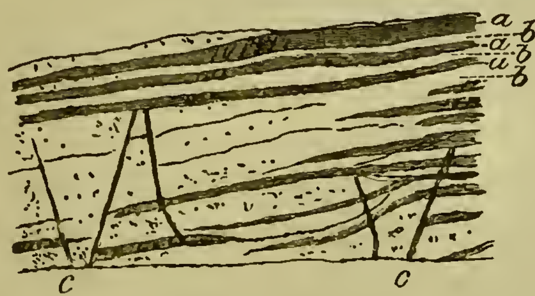


FIG. 5.—Section on the slopes of the old Volcano of Santorin (Fouqué).
a. Lava flows; *b*. Permeable scoriæ and ashes; *c*. Dykes.

The hydro-geological conditions of a volcanic mountain during the period of repose are of the same character as those ordinarily obtaining in Sedimentary strata, but whenever an eruption takes place these conditions are disturbed, and a special class of phenomena ensue. (See Plate 1.)

After a period of rest, the chilled superficial plug of lava in the volcanic duct will be of a thickness proportionate to the duration of that period, and when the upward pressure of the molten lava beneath begins to exert itself, the resistance will be in a ratio to the thickness of the plug. If thin, it will soon yield; small cracks and fissures will be gradually formed, into which the water lodged in the beds around, or may be in the crater, will find its way by slow degrees, causing an increase in the discharge of vapour, and giving rise to detonations, small at first, but increasing gradually as the heated lava breaks through the crust. Should, on the other hand, the plug be thick, it will not yield so readily to the pressure of the ascending column of lava; but when the tension has reached a certain point it will rupture more or less suddenly, forming deep fissures through which the water will be precipitated into the molten lava beneath, in quantity sufficient to produce those powerful and paroxysmal explosions with which the eruptions usually commence after lengthened periods of rest.

As a consequence of these detonations and explosions the fabric of

the mountain is shaken—the underground waters suffer disturbance, old water-channels are sanded up, new channels are formed—and the waters are dislodged and driven to seek fresh beds and fresh lodgments. These effects are necessarily most strongly felt in the rocks around the centre of eruption, and it is there that they undergo the maximum of displacement and fissuring; and as the water lodged in that part of the mountain flows into the volcanic duct, it flashes into steam, and is driven out in continuous explosions. Thus, the water stores immediately surrounding the central duct and crater, become gradually exhausted, and their level is more or less lowered. As this loss proceeds, the water lodged in more distant parts of the volcanic mountain flows in to supply the void, and the explosions will be violent and prolonged, according to the available volume of water present in the mass of the mountain. As these central water stores are driven off and become exhausted, and the level of the underground water is gradually lowered, there must necessarily be an influx from the circumference of the mountain to replace the loss caused by the central explosions, and this will continue so long as the central body of water is kept by the eruption lower than in the strata and fissures at a distance. These different hydraulic conditions are represented by the diagrams—sections 1, 2, 3, Plate I.

In these diagrams *v* represents the mass of volcanic materials; S the sedimentary strata; *p* the permeable strata; *m* the impermeable strata; *a*, *b*, *c* the normal level of the underground waters in the volcanic mountain; and *l* their level in the sedimentary strata. The arrows show the direction in which the waters flow under the normal and also under the altered conditions caused by the eruption. In section No. 1 the points *a* and *c* are fixed levels, while *b* fluctuates according to the amount of rainfall and to the length of the intervals between the eruptions. Its height above *a* and *c* depends upon the distance from those points and on the resistance of the materials through which the water percolates. This of course is apart from any exceptional interfering causes. The flow of water in *v*, section 1, will, under normal conditions of repose, be from the centre towards the circumference, and it will escape at the lowest levels; and if there are no lower levels inland, the whole direction will be seaward. In this section, however, the depression at *c* allows of an escape of some of the water on the inland side of the mountain.

As the level of *b* is lowered by the discharge of water into the duct of the crater, the water first ceases to escape at *a* and *c*, and then the adjacent body of water below that level sets in with an inward flow towards the central duct, as shown in section 2; for it is a well-known fact that in masses of partially resisting strata, such as the Chalk or the New Red Sandstone, excessive pumping (or the removal of water faster than it can be replaced from the surrounding strata) causes

a depression in the line of water-level in the form of an inverted cone, large in proportion to the amount of friction, and this continues until, on the cessation of pumping, the water gradually recovers its normal level by influx from the surrounding beds. The discharge of water from the crater is an analogous operation, and must be attended with the same consequences.*

This flow of water towards the volcanic centre is greatly facilitated by the dykes radiating from that centre, and which, intersecting at right angles the several water-bearing masses, serve as conduits to carry the water into the main duct of the volcano. Nevertheless, there may be some areas so isolated as to escape. If, however, a large fissure were formed through the head of water *ab* or *cb*, and happened to open out on the slope of the mountain at a level lower than the water-level in the interior of the mountain, then the escape of water would be outwards, and its volume would be in proportion to the mass of the mountain above that level, or to the height of the water-level at *b*. Such a fissure, probably during an exceptionally high water-level, might account, as before mentioned, for the flood on the slopes of Etna in 1665, and it is possible that the same cause may have produced some of the great water and mud discharges recorded of other volcanoes.

The progress of the eruption by which the level of *b* is gradually lowered finally determines the whole of the available drainage of *v* into the central cavity or duct: and if any portion of *v* be below the sea-level, and that portion contain any permeable beds, or if it be traversed by any of those radial dykes, which, at the high tide of *b*, carried its waters into the central duct, then whenever the level of *b* descends below the point of the escape of the fresh inland waters into the sea, the same permeable strata or the same dykes will serve to carry the salt water from the sea to the central area.† So also, should any fissures, under these circumstances, open at the sea-level after the higher inland head of water is drained, then the water from the sea will flow into that fissure and be carried inwards into the mountain. Professor Moseley mentions‡ a submarine eruption, that in 1877 took place off the Hawaiian coast, in a depth of from 150 to 400 feet of water, 50 miles from Mauna Loa, during which a fissure, in all

* The vapour of water constitutes by far the largest part of the elastic fluids given off during eruptions, probably $\frac{950}{1000}$ or even $\frac{999}{1000}$ of the whole. M. Fouqué estimated that the quantity of vapour projected from Etna in the eruption of 1865 amounted to the large quantity of 22,000 cubic mètres, or about five million gallons daily.

† Just as wells adjacent to the coast and deeper than the sea-level are subject to an influx of sea water if the pumping is carried too far, or the level of the springs too much lowered.

‡ "Notes by a Naturalist on the 'Challenger,'" p. 503.

probability connected with this eruption, opened on the coast. This fissure was traced inland from the shore for nearly 3 miles, varying in width from a few inches to 3 feet. "In some places the water was seen pouring down the opening into the abyss below." This is not strictly an analogous case, but I mention it to show how the activity of the eruption may be promoted by the influx of surface waters.

Similarly, should the water-level in and under the mountain fall below both the sea-level and also below the general level of the water, *l*, in the permeable strata *p*, then not only will the springs at the surface of *p* fail and the wells run short or dry, but the outward and seaward current will also be reversed, and the water will flow in from the sea to the seat of the volcanic disturbance, through the same channels as those by which the inland waters before escaped. This later condition of the eruption is represented in section 3, where the level of *l* in the strata *p* falls below the sea-level. With the fall of the water-level, *l*, the available supply of water becomes gradually exhausted or the channels of communication impeded, and this continues until, with the cessation of the extravasation of the lava, the eruption comes to an end.

To return to the first stage of the eruption. The lava, as it rends and crashes through the plug, comes into contact with the water lodged in the cavities and porous strata about and above the plug; explosions and detonations follow, violent in proportion to the supply of water. More or less of the lava is hurled into the air and scattered as scoriæ and ashes, and the explosions continue so long as water finds its way to the escaping lava, but as the supply becomes gradually exhausted the detonations diminish in power and number, until they finally cease from want of supply. But the extravasation of the lava may, and often does continue, long after this exhaustion of water supply, showing, as I believe, the independence of the two causes; for otherwise the flow of lava would be accompanied to the last with explosions and detonations due to the escape of the extruding agent.

This flow of water from the surrounding beds into the volcanic duct, its sudden flashing into steam and the violence of the explosions during the first period of the eruption, are easy to conceive; but greater difficulties attend the following stages when the column of lava has ascended higher and fills the duct, and the level of the underground water has become lowered. The only way water can then gain access is through the walls of the duct into the fluid lava as it ascends.

This involves some little-understood problems. Of the actual underground conditions we must ever be ignorant, and experiment at present guides us but a short way. Any inquiry must therefore for

the present be more or less conjectural. There can be little doubt that (as before explained) when the volcano is in a state of rest, the beds of volcanic materials surrounding the upper part of the volcanic duct are charged with water to a certain height, and also that, when the volcano stands on sedimentary strata, the duct lower down traverses a certain number of water-logged strata, where the hydrostatic pressure is considerable. For the water to rise to the height which it does at the Naples wells requires a pressure of not less than 50 atmospheres; but the static pressure of the column of lava in the crater of Vesuvius at the depth at which the water-bearing stratum there lies (1520 feet), during a central eruption of the lava, is, of course, far in excess of this. The introduction of the water into the lava must therefore depend on other conditions than hydrostatic pressure, such, for instance, as capillarity, or the elastic force of vapour. Although this increases so rapidly, yet as the law of increase at temperatures exceeding 436° F. has not been experimentally determined, and we have to deal with temperatures approaching to or equalling the melting point of lava, which is not less than 2300° F., we can only infer what may possibly be the consequences of the passage of a volcanic duct through water-bearing strata; and our remarks on this point must to a certain extent be taken as merely suggestive.

Under great pressure and friction water may continue to circulate underground until its critical point is reached, or until a point is reached when the elastic force of vapour, or of its disassociated gases, exceeds the hydrostatic pressure. In the former case, taking the critical point of water at 773° F., the depth would be about 35,000 feet, but of the limits of the latter we are ignorant.

If at a depth say of 5000 feet, or at any other depth, a water-bearing stratum should underlie a volcano, the temperature of the water in that stratum will, independently of its temperature of depth, rise rapidly as it approaches the volcanic duct, and pass progressively through an ascending scale until a temperature of 700° to 800° F., or higher, is reached. We will assume that at some point the force of the elastic vapour counterbalances the hydrostatic pressure, and stays the further approach of the water. In this case, and supposing the volcano to be at rest, the only underground effect would be that the water to a certain distance, *n*, fig 6, from the duct, would under that high temperature be at its critical point, or in some state of maximum tension and pressure. This being effected, there will be no further change so long as a state of equilibrium is maintained, and the pressure of the lava at rest in the duct D remains equal to the elastic force of the superheated water or vapour in *n*. If, however, that state of rest is disturbed, and the lava in the duct begins to move upwards, as represented in fig. 7, then, whatever the

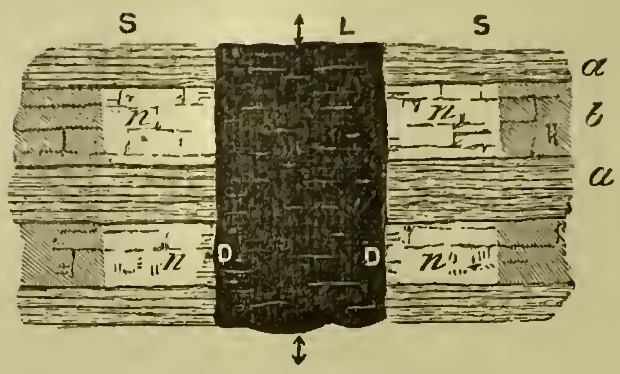


FIG. 6.—Lava column in a state of rest.

S. Sedimentary strata ; *a.* impermeable ; *b.* permeable. L. Lava in duct.

pressure may have been, the change from the static to the kinetic immediately destroys the balance; the lateral pressure of the lava, L, in the duct is no longer equal to that of the superheated vapour in *n*, which is therefore driven into the yielding mass of molten lava and so ascends to the surface.

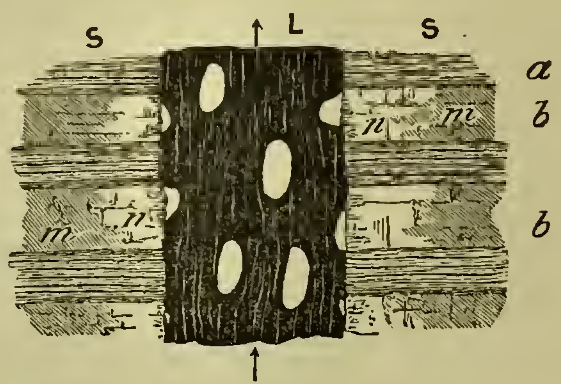


FIG. 7.—Lava column during flow.

As the escape of this vapour of maximum tension relieves the pressure on the water in the shaded part *m*, a portion of this water is at once driven in to replace it; and so long as the pressure of the column of lava in the duct is less than that of the vapour or water in the state in which it exists at *n*, so long will successive increments of the vapour be driven into the lava and cause continuous explosions.

The only limit to the depth at which the introduction of water into the duct can be effected will be that at which the general underground percolation of water is stayed in the manner before explained—that is, by the increase of the temperature due to central heat—a depth far in excess of that where we are supposing the introduction of the surface waters to take place.

With regard to the lesser depths and lesser general temperature of the water in the strata surrounding the higher parts of the volcanic duct—capillarity will there continue to force the water forward so long

as the underground water stands at a sufficiently high level. Mallet was of opinion* that capillary infiltration goes on in all porous rocks at enormous depths, and that the deeply seated walls of the volcanic ducts leading to the crater, if of such materials, may be red hot, and yet continue to pass water from every pore (like the walls of a well in chalk), which is flashed off into steam, and, unable to return by the way the water came down, escapes through the duct and crater. For my own part, I do not think this can happen during a state of undisturbed statical pressure, but that it follows on any disturbance.

That capillarity exercises a very important influence on the underground percolation of water is undoubted. To a certain point it has been proved experimentally by M. Daubrée,† who found that water placed on a disk of fine-grained (Triassic) sandstone,‡ fastened over a vessel filled with steam under pressure of nearly two atmospheres, infiltrated into the underlying vessel against that pressure. He further noticed that in consequence of the heat the action was more rapid than it otherwise would have been; and—making the experiment inversely—he observed that vapour placed under a pressure of several atmospheres in the lower vessel, did not transude through the disk left dry on the upper surface. As before pointed out, however, capillarity is adversely affected by a rise of temperature, and is comparatively inoperative at high temperatures.

Under these circumstances, it is conceivable that water may readily be carried down through the upper cooler strata to the proximity of the volcanic duct. But no amount of available vapour tension could force it back through the same depth of strata against both friction and capillarity. At the same time when the elastic tension of the vapour of the water reaches the point either of critical temperature, or such higher temperature that it exceeds the hydrostatic pressure, the further progress or descent of the water will be prevented. The influx of water to the volcanic duct is to a certain point effected under the same conditions as those which effect its general descent to depths through the earth's crust. But at this point, whatever it may be, other causes come into operation, which, while the descent of water to the *volcanic foci* beneath the solid crust remains an impossibility, renders its introduction into the *volcanic ducts*, even at considerable depths, possible. In any case, when an equilibrium is established between the vapour tension and the hydrostatic pressure, no change will take place unless that condition of equilibrium be disturbed. Such a cause exists in the case of a volcanic duct.

In fig. 7 the surface-waters pass in the usual manner through the strata *b* to some point *m*, where the heat from the lava L in the duct

* Palmieri's "Eruption of Vesuvius in 1872." Mallet's Introduction, p. 52.

† "Géologie Experimentale," 1879, p. 236.

‡ The absorbent power of this rock = 6·9 per cent. by weight.

gives the water an elastic force sufficient to bar its further progress, and fills the space *n* with vapour at an excessive tension, or with water at the critical point. This tension has determined a state of equilibrium which, so long as no change takes place in the opposing surfaces of the vapour and the lava, is maintained without change. If, then, anything occurs to weaken the resistance of one of the surfaces, and equilibrium be destroyed, the surface, if elastic, will yield. Thus, so long as a volcano is at rest, the pressure exercised by the column of lava L against the sides of the duct counterbalances the tension of the vapour at *n*. But, when the lava is forced upwards and flows past *n*, the statical pressure at that point is so far lessened that the tension of the vapour now exceeds the resistance of the lava at the same point, and the vapour is driven into the liquid lava L and rises with and through it to the surface. At the same time the sudden elastic expansion of the vapour lessens the pressure on the water at *m*, which therefore becomes in turn explosive, and as this water is replaced by a portion of that which is pressing forward from the water-head in *b*, this action will be repeated so long as the water supply lasts and the disturbing causes continue in operation.

The influx of water into the volcanic duct will also be materially influenced by the changes of level, or oscillation, which the column of lava undergoes during eruptions. For the variation of pressure caused by this state of changing equilibrium allows the vapour pressure to predominate at one time, while the resistance to it by the column of lava will be in excess at other times.

The explosion of steam into the lava involves, amongst other effects, disturbances of the encasing strata whenever any portion of the water or vapour explodes behind blocks of rock forming part of the walls of the duct. In fissile or porous sandstones, where the water cavities are small, it may be supposed that a minimum dislodgment of the materials composing the strata takes place. But if, instead of soft

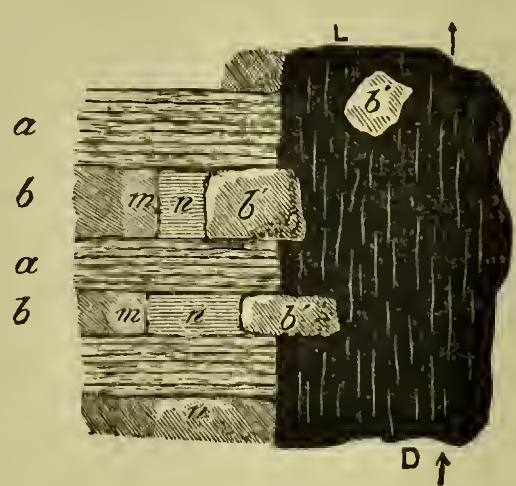


FIG. 8.—Projection of blocks from the permeable Strata *b* into the ascending lava (one side only is represented).

or incoherent sandstones, the strata consist of bedded compact limestone or other rocks, as represented in diagram, fig. 8, through which the water passes in open fissures, then the result will be different; for the rock being divided horizontally by the planes of bedding, and vertically by joints and cracks constituting the fissures in which the water is lodged, when the water surrounding the blocks b' explodes or flashes into steam they will be forced or blown out with the escaping steam into the lava current L, in which they will be carried to the surface and ejected with the lava-scoriæ by the explosions of the elastic vapour. The cavities formed by the expulsion of the blocks b' are immediately injected with the lava from column L which eventually consolidates there. At the next eruption, when the former conditions of water level have been restored, the renewed explosions at m n will expel not only other portions of the strata, but also portions of these intruded masses of lava. It is thus that in the earlier eruptions of Vesuvius, which form the slopes of Somma, blocks of altered limestone derived from the underlying Tertiary and Cretaceous strata are common; they are scarcer in the later eruptions. It was while forming the walls of the duct, and in contact with the molten lava and heated water or vapour, and not while imbedded in the lava, that these rock masses probably underwent that metamorphism which, in the case of the Vesuvian lavas, resulted in the formation of the very varied group of minerals met with in the ejected blocks of Somma. Similar metamorphosed blocks are found in the old lavas of many volcanoes (Santorin and others), whilst the blocks of quartz mica-schist occasionally met with have undergone little or no change.*

Besides these blocks of Sedimentary rocks, there are also found in the more recent lavas of many volcanoes blocks of lava having the character of the early erupted lavas. Fouqué mentions that in the eruption of Santorin in 1866, there were enclosed blocks of a lava of which the composition differed considerably from that of the flowing lava, and that they contained the minerals common in the old lavas of that island.† It is difficult on any other hypothesis to account for the presence of such blocks.

I consider, therefore, that a volcanic duct passing through a certain number of permeable strata charged with water, and through volcanic matter also charged with water below a certain level, is surrounded at these points by, as it were, an explosive material under repression, which only requires a disturbance of the equilibrium, under which it exists when the volcano is in a state of repose, to explode with violence. Further, as the superheated vapour from each point of contact forces its way into the ascending lava, the contiguous portion of highly heated water behind it is driven forward, replacing that which has

* Fouqué, "Santorin," p. 10.

† *Ibid.*, p. 12.

just escaped, while another portion of the water filling the stratum is pressed forward to take the place of the exploded portion. If the lava still continues to ascend, the in-forcing of the vapour and the explosions of successive portions of water succeed almost uninterruptedly, and the volcanic duct thus becomes the centre to a battery discharging at many levels and keeping up an incessant volley; for the supply of water at first is comparatively unlimited, and being renewed as quickly as it is exploded, there is no cessation in the action until the source is drained or stopped or the lava ceases to flow. If the water is lodged at such a distance, n, from the sides of the duct that it explodes behind blocks or fragments of rocks, or of older lava lodged in the cavities left by previous removals of portions of the rock, then such blocks will be blown and driven into the outflowing lava current. This seems to be a more probable explanation than that of their being torn or wrenched off the sides, although in the first stage of a new volcano there may often be great mechanical action and ejection of *débris* in clearing the passage, as in the case of the large quantity of *débris* of Devonian strata in so many of the old volcanoes of the Eifel.

In considering the various phases of this problem, it is, however, only too apparent that while the hydro-geological conditions admit of investigation on known principles, the thermo-dynamical conditions are involved in much obscurity, and are more hypothetical. The warrant for any hypothesis depends, however, upon whether the observed phenomena accord with the inferences that should follow on the assumptions, and for this I think sufficient cause can in this instance be shown. For the more or less deep-seated subterranean detonations and thundering that accompany most eruptions, and the paroxysmal explosions accompanied by enormous ejections of steam and ashes from the crater, are the necessary consequences of an influx of water into the volcanic duct under the conditions we have described; while a term is placed to the continuance of the eruption in the circumstance that the water supply being external and independent, whenever that supply is exhausted by expulsion through the escaping lava, the explosions must cease, although the eruption of lava may proceed for a longer period. The hypothesis agrees also with the fact that as a rule the eruptions are more paroxysmal the longer the interval of rest, for the filling of the underground reservoirs exhausted by the previous eruption is a question of time, and the greater their water-stores, the greater and more powerful the explosions.

The apparently conflicting phenomena of Ehrenberg's discovery of fresh-water diatoms in the volcanic ejections of some islands, and of marine diatoms in others, admit also of ready explanation on this hypothesis, for so long as the inland underground waters due to the

rainfall stand higher, which they must do whenever the land is even only a few feet above the sea level, so long will those waters dam back and keep out the sea-water, but whenever their level is brought below that of the sea level, then inevitably will the sea-water flow inland until the level is restored. Thus fresh-water remains accumulated during a period of repose, may be ejected during the early stages of the eruption, and may be succeeded by marine ejections when the exhaustion of the fresh-water springs leads to the influx of the sea.

There are difficulties in adapting this hypothesis to volcanoes in a state of permanent action such as Stromboli and Kilauea, but they are not more formidable than those presented on other hypotheses.

In both those volcanoes there is a maintained state of slight unstable equilibrium—a constant oscillation of the lava in the volcanic duct coupled with a small loss, whether in the form of ejected scoriæ or of slight occasional overflows of lava. As these conditions are permanent, they would induce in the manner before described a permanent influx of water either through permeable strata at depths, or by soakage of surface or sea water through the loose volcanic matter above; and as owing to this incessant drain, the underground reservoirs would not have time to fill to their full extent, so it is probable that the influx of water would always be small, but sufficient to maintain the slight and constant disengagement of vapour bubbles that goes on. Mallet says that there is a perennial spring on Stromboli at a higher level than the crater.

The independence of neighbouring volcanoes also presents another difficulty. If, however, the volcanoes of Southern Italy or those of Hawaii are, as suggested by Dana, on separate lines of fissure, it is possible that on the assumption of excessive viscidity of the lava, friction may oppose greater resistance along the horizontal planes which separate them at depths, than along the vertical column of ascent in which the increasing fluidity, as the pressure lessens, diminishes the friction. This is merely a suggestion. Although seemingly independent, there is occasionally both in the Italian and in the Hawaian volcanoes, symptoms of sympathetic action.

On the hypothesis advanced in these pages, a reason is also afforded why a greater volcanic activity should be maintained along coast lines than inland, in the circumstance that when the inland waters which feed for a time the explosive action are exhausted, they are succeeded through their now deserted channels, by an influx of sea water that serves to keep up for a longer period the state of volcanic activity, and maintain passages open for the extrusion of the lava. It is thus that the great inland volcanic areas of Auvergne, the Eifel, Hungary, and Central Asia have, on the withdrawal of the surrounding waters, become gradually extinct, and that the great volcanoes of the present day have settled in ocean centres, or along coast lines.

In mostly all of existing volcanoes, there is clear evidence of the access of sea water in the presence not only of the chlorides and other products of its decomposition in the emanations from the lava, but also in many cases of sea salt itself. Not, however, that the presence of sea water is necessary or is always present; for the vast stores of underground water in the Andes, and the great distance from and height above the sea of so many of the South American volcanoes, render it probable that they are in the main dependent upon inland water supplies, and this is confirmed by the researches of Boussingault, who was unable to detect in the fumaroles he examined any traces of chlorides.

But if water only plays the secondary though important part I have assigned to it, to what are we to attribute the motive power which causes the extravasation of the lava? This involves questions connected with the rigidity and thickness of the earth's crust, that we will proceed to consider in their geological bearings.

§ 6. *Thickness of the Earth's Crust from the Geological Standpoint.*

Geologists and physicists still hold from their different standpoints divergent views respecting the thickness to be assigned to the crust of the earth. Although the present stability of the earth's surface renders it evident that the hypothesis of a thin crust resting on a nucleus altogether molten and fluid is untenable, it is equally difficult to reconcile certain geological facts with the hypothesis of a globe solid throughout, or even of a very thick crust.

Nor have the phenomena of the tides yet been determined with sufficient accuracy to settle definitely the moot question whether the rigidity of the crust is perfect, or whether it yields to some very small extent to the deformation that might be caused by slight internal tides. Therefore, while on this ground alone, even if the data were not otherwise insufficient, there are, on the other hand, certain geological phenomena, volcanic phenomena among the rest, which are not only incompatible with an entirely solid globe, but which would seem to be explicable only on the hypothesis of a thin crust and a slowly yielding substratum. Of course it is also open to consideration, whether a crust and substratum of this nature would not, under certain conditions, offer sufficient resistance to produce a *quasi* rigidity such as would accord with existing physical conditions.

The phenomena on which on geological grounds I should chiefly rely in proof of such a substratum, and of a crust of no great thickness, are—

1st. The flexibility of the crust as exhibited (*a*) in the uplift of mountain chains, and (*b*) in the elevation of continental areas.

2nd. The rate of increase of temperature with the increase of depth from the surface.

3rd. The volcanic phenomena of the present day, and the welling-out of the vast sheets of trappean rocks during late geological periods.

a. It is important for our object to note that not only has mountain-uplifting gone on through all geological time, but that many, if not most, of the great mountain chains have been raised during the latest geological periods, and that compressed uplifts have not been confined to any limited district, but have extended over the several continents and over both hemispheres. As instances of these may be named:—

1. The elevation of the Pyrenees, which, although commenced in Palæozoic times, attained its maximum intensity and development in Oligocene, while minor movements continued to Miocene times.
2. The main elevations of the Rocky Mountains and portions of the Andes took place during the Tertiary period, and they were raised to their present height so late as in Miocene and Pliocene times.
3. Although considerable elevations of the Himalayas are of Pre-Tertiary date, the researches of the geological survey of India* show that the special great Himalayan disturbance is of Post-Eocene age; while in the Sub-Himalayan ranges, there is a large amount of disturbance of Post-Pliocene date.†
4. The elevation of the main axes of the Alps (although, like the others, began earlier) took place in Miocene times, and was prolonged to as late as the Post-Pliocene period, or to the time immediately preceding the comparatively recent Quaternary period.

It is only necessary to look at the section of any mountain chain to see the enormous amount of squeezing and crumpling the strata have invariably undergone, and the succession of folds of vast magnitude into which they have been thrown. In the Alps there are seven, if not more of these great folds, each constituting a mountain chain. In a straight line across they measure about 130 miles; but, if the strata were stretched out in the original planes, it is estimated that they would occupy a space of about 200 miles.

Le Conte states that the coast range of California consists of at least five anticlines, and as many synclines so closely compressed that a width of 15 to 18 miles of horizontal strata has been reduced to 6 miles.

* Medlicott and Blanford's "Geology of India," pp. 569, 570.

† It is a question even whether the earth movement along this great axis of elevation has yet wholly ceased.

These are common geological facts. I need add but one more instance on account of the magnitude of its scale.

Professor Clarence King, speaking of the plication of those parts of the Rocky Mountains which lie in Wahsatch and Uinta, estimates that the folds there measure 40,000 feet from summit to base.* What must have been the contraction in horizontal distance where the strata form not one but several folds, the crown of whose arches attain a height to be measured by miles!

It is difficult to see how these corrugations of the earth's crust are to be accounted for, unless we assume that the crust rests on a yielding substratum, and that it is of no great thickness. For if the earth were solid throughout, the tangential pressure would result not in distorting or crumpling, but in crushing and breaking. No such results are to be seen, and the strata have, down to the time of the youngest mountains, yielded, as only a free surface-plate could, to the deformation caused by lateral pressure. Freedom and independence of motion are evident in these wonderful contortions and inversions of the strata, and for that result a soft and yielding bed on which the crust could move as a separate body is necessary. Nor is evidence wanting that such a yielding plastic bed does exist, for rising up in the central axes are not unfrequently masses of crystalline rocks, which were then or shortly anterior in a viscid state, or else the strata are penetrated by dykes and veins of igneous rocks indicating a still greater fluidity of the broached fundamental base.

These facts are so patent to geologists that it may seem almost superfluous to adduce them. Let us suppose not entire solidity, but a crust 800 miles, or even half 800 miles thick. What would be the magnitude of a mountain chain resulting from the crumpling and upthrow of such a mass of rock? Where have we evidence in the latest of our mountain chains of the existence of such masses? Nowhere do the disturbed and tilted strata point to a mass more than a few miles thick, for the whole of the sedimentary and metamorphic rocks are often uptilted, together with a portion of the molten rocks on which they rested. Had the crust had the more excessive thickness suggested by physicists and by some geologists, we should have had mountains if not of greater height, at all events of greater breadth; for if a solid plate of any kind be broken and the fractured edges turned up by reciprocal pressure in presence of a viscid resisting material beneath, the width of the protruding mass will bear a definite relation to the thickness of the plate. If, on the other hand, the plate is sufficiently pliable to yield without fracture and be bent into folds, the height of the arch and the width across the fold will in like manner be proportionate to the thickness of the plate.

* "Geology of the 40th Parallel," vol. i, p. 761.

Where have we evidence, even in the most recent of mountain chains, when the earth was approaching its present conditions of rigidity, of a shell of 700, or 500, or 100, or even of 50 miles thick? Would it not rather appear that a crust of 30 miles is even in excess of what the height and breadth of any mountain chain would, on this finding, indicate?

To the first part of the argument, it may be rejoined that the existence of a thinner crust and of a fluid nucleus is not contested in the various geological periods, and that the conditions of solidity and rigidity are only applicable to the globe as it at present exists. But the observation loses its point when we consider that the cooling must have been slow and gradual throughout all time,—that the formation of mountain chains has been intermittent with long intervals,—that the last-formed chains show no change in the character or diminution in the forces to which they are due,—and that there is nothing to indicate such a sudden accession of solidity in the earth as would be involved by the assumption of the free play of the crust during Tertiary times and its entire rigidity now; whilst, on the other hand, other forms of the forces coordinate in a cooling globe still continue in visible action. If one form of a force dependent on a common cause remains in operation, we are scarcely justified in assuming that another consequence of the same cause, though dormant, is extinct. Our limited experience suffices to make us acquainted with the more persistent effects, but fails to compass those which are intermittent.

b. With respect to the other analogous forces in operation now and in times immediately preceding our own, they likewise indicate a yielding substratum—although the disturbances at present caused by them may not result in the fractures and contortions involved in mountain-forming, and which are only the effects of prolonged and extreme tension. I allude to those wide-spread movements which result in great superficial or continental upheavals—movements which, of frequent occurrence in all geological times, have not altogether ceased in our own times. Our object is, however, with the later periods only. It will be sufficient if we go back towards the close of the Tertiary period.

We have merely to look at a geological map of the world to see that a very large portion of the existing continents have been under the sea during the Tertiary period. South-eastern England, a large portion of France, great part of Spain and Italy, and the whole of Central Europe, have, since the Eocene period, undergone movements of elevation *en masse* with little disturbance to the strata over large areas, and these have been prolonged down to Miocene and Pliocene times. In the same way the elevation above the sea of great part of Asia Minor and Mesopotamia is of Post-Miocene age. Nor has the

yielding of the crust during this late geological epoch been confined to these limits. Great parts of India, Australia, and of the seaboard of North and South America, have been under the sea and raised at various intervals during the whole of the Tertiary period.

But it is not these movements—great and general as they were—that so immediately concern the question before us. Our object is to show that the flexibility of the crust, which is exhibited in all geological periods, has been continued without break and over large areas down to the latest period, and that the older changes link on to changes in progress in our own times—changes admitting of a measurement which enables us to realise their importance.

The presence of shells of recent species at certain elevations in Central England and Wales prove that those areas have undergone an elevation of not less than 1400 to 1500 feet after the inset of the Glacial period. Ireland and Scotland have undergone changes little less in the same period; and so likewise has the North American continent. The rock of Gibraltar has been raised 1400 feet or more at even a later period. The *massif* of Scandinavia, the long coast-lines of the Pacific side of South America, have been raised 500 or 600 feet or more during the life of existing species of Mollusca. Over portions of the Pacific basin islands have been raised 200 to 300 feet or more, and the coasts of Arctic America and Asia exhibit conclusive evidence of similar recent elevation. These movements of elevation, which bring us down to the threshold of the present times, link on without break in the latter areas (and many others might be named), with the changes of level which some of those areas are still undergoing.

Changes of level have been ascribed by some to the change of temperature at depths, caused by the shifting upwards of the underground isotherms, in proportion as the strata have increased in thickness by the successive addition of fresh sediment. This, as suggested by Babbage and Herschel, may be a true cause under certain conditions of thick accumulation of strata, but must necessarily, as the expansion of rocks by heat is so small, be limited to moderate vertical displacement, and fails to explain the greater changes of level to which we have just referred, for neither in the Old nor in the New World do the later Tertiary strata exceed, as a rule, a thickness of 1000 to 3000 or 4000 feet, so that the difference of temperature in the strata so covered up would not usually exceed 20° to 100° F., and would rarely attain to a rise 150° F. Supposing this to affect an underlying mass of rock, say 100,000 feet in depth, the effect would be to increase its dimensions vertically from about 10 to 100 feet only. This also is on the assumption that the underlying mass of rock remains stationary; but if, whilst the accumulation of strata proceeded, the area itself, as has usually been the case, subsided, the only effect of expansion of the

mass, unless it all took place at once after the deposition of the overlying strata was ended, which is impossible, would be *pro tanto* to diminish the rate and extent of subsidence. Further, alterations of level arising from this cause are not likely to have taken place in Glacial and Post-Glacial times, as the sedimentary matter then deposited was generally limited to a few irregular masses of sand, gravel, and shingle, or to a few raised beaches and shell beds only a few feet in thickness; while the submarine beds rarely reached a thickness of more than 300 or 400 feet.

The next point we have to consider is, that of the increase of temperature with the increase of depth. On this, there is a general agreement as to the fact, but a difference of opinion as to the rate of increase and in the inferences to be drawn from the observations. The rate of increase is found to differ very materially at different places, varying in round numbers from 30 to 100 feet for each degree F., or with a mean by some taken at 50 and by others at 60 feet; and conclusions have been drawn by some geologists from these observations that the nucleus of the earth is in a state of fluidity at a depth of 30 miles, whereas others have considered the facts not incompatible with a crust of 800 miles or more thick.

The variation in the rate of increase with depth is influenced not only by the variable conductivity of the strata, but depends also upon so many disturbing causes, that while all the observations tend to prove the general fact of an increase of temperature with depth, very few can be relied upon to give an exact measure of that increase. Notwithstanding the care taken by some of the earlier and all the later observers against these disturbing causes, these are so numerous and often so difficult, if not impossible to guard against, that only a limited number of observations can be relied upon to give the exact data required. I have gone elsewhere* into the various considerations affecting this question, so that they need not be repeated here. The conclusion that I have arrived at is, that the observations that can be best relied on show an increase of not less than 1° F. for every 48 feet of depth, and which there is some reason to believe may be even more rapid.

Whether or not the rate of increase diminishes or increases with the depth is a question which requires further investigation. The few observations that have been made throw little light on the subject. These are given in the paper before referred to. They certainly do not tend to prove that there is any diminution in the rate of increase of temperature. There are some reasons on the contrary which would lead to an opposite opinion.

* *Ante*, p. 1.

The received conductivity of chalk, sand, clay, and some sandstones, through which so many of the bore-holes and shafts in which the observations have been made have been carried, is low. It has been inferred in consequence that the isothermal lines of depth are closer together in these rocks than they would be in the underlying crystalline and igneous rocks, and therefore that these surface rocks give us a more rapid rate of increase than would be found to obtain at greater depths. But it must be remembered that in general the experiments on the conductivity of rocks have been made with specimens carefully dried; whereas all underground rocks hold a certain quantity of water, the water of imbibition; and further below a certain level—that of the line of water-level—they are charged with a further quantity of water, or the water of saturation. Every bore-hole or shaft has to do with rocks under these conditions. Now, the experiments of Messrs. Herschel and Lebour show that there is a remarkable difference between the conductivity of rocks in their dry and wet state. Thus, taking the rocks just named, these differences are as under, k being the thermal conductivity, and r the thermal resistance.

	Dry.		Wet.	
	k.	r.	k.	r.
Quartzose sand......	0·00105	952	0·00820	122
Clay	0·00250	400	0·00370	270
New Red Sandstone..	0·00250	400	0·00600	166 ?

It appears by this that sand, which is one of the worst conductors when dry, becomes one of the best when wet, being only exceeded by rock salt, vein quartz, and quartzite; while the average conductivity of the three substances above named exceeds when wet (k=0·00597, r=186) that of many igneous rocks. The average of five common varieties of the latter gives k=0·0524 and r=196; with five varieties of granite the average is k=0·00584 and r=173, and taking together several varieties of Palæozoic limestones k=0·00572 and r=177.

Experiments on wet chalk, oolite, and coal-measure sandstones are wanting, but as the water of imbibition of these several rocks is as under, it is to be inferred that when wet their conductivity would be raised in proportion with that of the others:—

	Per cent. of water.		Per cent.
Coal shale	2·85	Chalk........	24·10
Sandstone..	4·37 to 13·15	Cal. freestone.	16·25

On the other hand, the harder crystalline and igneous rocks imbibe but little water:—

Granite	0·06 to 0·12	per cent.
Devonian limestone	0·08	,,
Basalt	0·33	,,
Slate	0·19	,,
Quartzite	0·66	,,

Then, again, the conductivity, even when dry, of the "ganister" and other hard Coal-measure sandstones is found to be higher than that of either the metamorphic or igneous rocks, averaging for four varieties $k=0·00737$, $r=136$.

It seems, therefore, probable that the unaltered sedimentary strata are often, under their normal underground conditions, as good, if not better, conductors of heat than the crystalline and igneous rocks which constitute the greater proportion of the solid crust of the earth, and, if so, the thermometric gradient would rather tend to become more rapid in passing from the former into the latter than otherwise.

But there is another cause which when the subject comes to be more fully investigated will have to be considered—that is, the change of conductivity produced by heat. Forbes found that the conductivity of iron varied with the temperature as under :—

0° C.	0·0133
100 ,,	0·0107
200 ,,	0·0082

This shows a percentage decrement of the decrease of conductivity of iron between 0° and 100° C. of 24·5, which agrees nearly, according to Professor Tait, with the empirical law that the conductivity is inversely as the temperature. Looking at other physical properties which the metals and rocks have in common, it is not improbable that they may have also this other property, although, no doubt, in a very modified form. It is the more probable, inasmuch as the proportion of iron present in the igneous rocks (commonly 10 to 15 per cent.) is larger in those which are supposed to be the more deeply seated; while considering how largely the density of the mass of the earth is in excess of the density of the crust, there is reason to believe that the proportion of the metals increases with the depth. This would produce an important effect on the thermometric gradient.

A large number of the observations on temperatures at depths have been conducted in carboniferous strata consisting largely of sandstones of high conductivity; and others through chalk, clays, and sands of which the conductivity becomes high when wet,—and wet they must be at even small depths beneath the surface. On the other hand, the crystalline and igneous rocks are so hard and compact and absorb so little water, that their conductivity can be little influenced by this cause.

After eliminating those observations where the results are affected by some of the various causes of interference, it would appear that the sedimentary rocks *in situ* do not possess a lesser power of conduction than the igneous and crystalline rocks which underlie them, so that the rate of increase of temperature need not on this account be less rapid. This is especially a conclusion which may be drawn from the deep (4172 English feet) and remarkable boring of Sperenberg, where the bore-hole first passed through not quite 300 feet of gypsum, and then entirely through rock salt of which the conductivity is extremely high (0·0128), exceeding that of any other rock; nevertheless, the rate of increase is 51·5 feet per degree F.* Had it been a rock of lesser conductivity the rate of increase could hardly be otherwise than more rapid.

Assuming a uniform rate of 1° F. for every 48 or 50 feet of depth, the heat at a depth of 28 to 30 miles would be such as to fuse the basic rocks, and this has often been taken as a measure of the probable thickness of the earth's crust. But there is the uncertainty just named whether the rate may not increase, while the phenomena before named indicate that this even is too great a thickness to be in accordance with observed geological facts?

May it not also be a question whether, as I have before suggested, the intense cold of the Glacial period has not so affected the outer layers of the earth's crust that to a certain depth the rate of cooling is now abnormally slow, owing to the excessive refrigeration the shell then underwent. If that be the case, would not the rate of increase of temperature at greater depths be more rapid than that which our observations on the chilled layers have led us to assume, so that the thickness of the crust might be even less than the 28 to 30 miles just named? Such a conclusion would be more in harmony with geological phenomena, as we shall proceed further to show.

The third objection to a thick crust is the difficulty of reconciling such a condition of things with the effects of volcanic action. This branch of the subject may be divided into the phenomena connected—1stly, with recent volcanoes; 2ndly, with the great outwellings of trappean rocks during the later Tertiary period; and, 3rdly, with the character of the changes of level in the areas so affected.

The first point relates especially to the apparent impossibility of a column of lava traversing a crust 800 to 1000 miles thick in consequence of the enormous pressure required, and without the loss of so much heat in such a length of passage as to cause the lava to lose its fluidity and consolidate before it could reach the surface.

To meet this difficulty Mr. Hopkins suggested that the solid crust contained at various depths beneath the surface cavities filled with

* "Brit. Assoc. Reports" for 1876.

fluid incandescent matter, either entirely insulated or perhaps communicating in some cases by obstructed channels, and that in these subterranean molten lakes the volcanic foci originate.*

To this view it is to be objected that the variation in depth from the surface, and the existence of separate molten lakes is not compatible with the singular uniformity as a rule of the volcanic rocks over the whole globe; again, lakes would be required co-extensive with large continental areas, and therefore there seems no object in the limitation; while further on this hypothesis there would seem to be no available cause for the extrusion of the lava other (but applying with greater force) than that assigned by Mr. Scrope, the objections to which I have already named.

Again, the enormous outwellings of trappean and volcanic rocks which took place at intervals during the Tertiary period and continued down to Quaternary times, afford evidence of the existence of a fluid magma underlying the solid crust, co-extensive not only with the existing volcanic outbursts, but also with these older eruptions, and spread the volcanic phenomena over areas so large and so numerous that it is difficult to conceive their isolation as separate and independent local igneous centres.†

In this country the great basaltic plateau of the North of Ireland is 600 to 800 feet thick, and extends over an area of about 1000 square miles; those of Western Scotland are of about the same extent, and it is certain that both had, before the coast denudations, a much wider range. In Central France there is a still wider basaltic area of yet more recent date. There are others of great extent in Hungary and in Central Italy. They cover also large tracts in Asia Minor, Africa, New Zealand, Australia, and America. But to confine ourselves to two instances on a grand scale we may take the great plateaux of Central India and of North-west America.

In India these plateaux stretch for a distance of 500 to 600 miles from north to south, and 300 to 400 miles from east to west, covering, according to the reports of the Indian Survey, an enormous area of not less than 200,000 square miles.‡ They have a general thickness of from 2000 to 3000 feet, and it is estimated that the total thickness of all the beds amounts to not less than 7000 feet. They are of late Cretaceous or early Eocene date, and consist of a succession of beds spread, no doubt, over a long period of time.

In North America vast sheets of basaltic rocks form the high plateau of Utah, while on the Pacific slopes immense regions have

* *Op. cit.*, p. 54.

† See also the Address of Sir Wm. Thomson, in Section A, Brit. Assoc., 1876, in which the evidence regarding the physical condition of the earth is reviewed.

‡ "Manual of the Geology of India."

been flooded by outpourings from fissures at successive times from the close of the Miocene down to the Quaternary period. In Columbia these basaltic rocks have a thickness of from 1000 to 3000 feet, and in parts of Colorado of not less than 4000 feet, and they stretch over a tract some 700 to 800 miles in length by 80 to 150 miles in width, and cover 120,000 to 150,000 square miles of surface.

Extensive as are the ejections of some volcanoes at the present day, and vast as are some of the individual lava streams, the sum total is small compared with these older extrusions. Lyell instances as amongst the most remarkable of the modern lava streams that formed during the eruption of Skaptán Jokul, in Iceland, in 1783. He states that it formed two branches of the relative lengths of 50 and 45 miles, and of the extreme breadths of from 12 to 15 miles, and of 7. Taking the mean breadth, we have an area of 500 square miles covered by the lava of this eruption, with an ordinary thickness of about 100 feet, and an occasional one, when it filled gorges, of 600 feet.

But we have no means of judging of the single flows of geological times; we can only take the total areas covered by recent volcanic eruptions, and compare them with the old basaltic outpourings. The two most extensive modern volcanic surfaces are those of Hawaii and Iceland. The thickness of the masses at the centre of eruption probably exceeds, though the average of the whole mass is certainly below, the thickness of the basaltic beds in the cases named above, but the areas covered by the volcanic materials show very different measures. The area of Hawaii is about 3800 square miles and is entirely volcanic, and that of Iceland is 37,800 square miles, of which the volcanic beds are said to occupy about one-third to one-half. At the outside, therefore, the modern eruptions are spread over no area larger than 20,000 square miles, or an area only equal to one-tenth and one-seventh of the old Indian and American basaltic areas.

Now, if these vast erupted masses had been derived from local molten lakes of moderate size and moderate depths, the extravasation must have caused a diminution in their masses which, as the loss could not be made good by drafts from adjoining areas, must necessarily have led to a caving in and subsidence of the crust above these lakes proportionate to the mass of the extravasated matter. But so far from this being the case, the areas of these great basaltic outwellings are almost always areas of elevation. The basaltic area of the Deccan forms vast plateaux which attain a height of between 4000 to 5000 feet, and although the intercalated sedimentary strata are mostly of land and freshwater origin, there is reason to believe from the circumstances that on the borders of the same district some of the associated beds contain estuarine remains, that the area was immediately prior to the eruption not much above the sea-level.

In America also the basaltic plateaux rise gradually to heights of from 2000, 3000, and 4000 feet, and in some cases even attain the height of 11,000 feet or more. Similar evidence, though on a much smaller scale, is afforded by the basaltic plateaux of Ireland and Scotland, of Central France, and of other countries which form relatively to the surrounding districts more or less elevated tablelands, raised above the sea-level mostly in Tertiary and many in very late Tertiary times.

It is impossible to attribute the elevation of these vast flattened domes to any secondary causes, such as expansion by heat of strata undergoing subsidence by transmission of the isothermals. The difference of level is, as before explained, too great. Besides, the crust in these areas must on the whole, so far from gaining in any part, suffer a considerable loss of heat by the very circumstance that the heat brought by the lava to the surface is lost by radiation. There would, therefore, be every cause for depression of the crust were the molten lakes local and independent. These areas of eruption are, on the contrary, areas of elevation—not as in mountain chains by lateral squeezing and an upward thrust along narrow anticlinal lines, but by elevation *en masse* of wide portions of the earth's crust possibly accompanied by fracture but without, necessarily, contortion.

We have, therefore, in the discharge of volcanic matter *primâ facie* evidence of the existence of molten matter beneath the surface, and, in the domed elevation of the surface, of a yielding substratum, fluid or viscid, underlying the solid strata. Further, it follows from the fact of the upheaval that the igneous rock ejected is not only replaced, but that it is replaced by a quantity larger than that which is lost by extravasation. This could only be effected by supplies from adjacent areas of similar matter—in other words, it indicates that there must be a common fluid or viscid substratum, yielding to depression in some areas, and to upheaval in others, the loss in the one case being counterbalanced by an addition and centralisation in others. Apart from the great movements which raised the basaltic area of the Deccan, Dr. Blanford* states that in the Indian Peninsula there is evidence bringing down movements of elevation to the extent of 100 to 200 feet to so late a period as the old raised beaches (of Pleistocene age) that, on the other hand, the presence of the Maldive, Laccadive, and Chagos groups of atolls and coral reefs in the sea to the south-west, points to slow depression; and that there is unmistakeable proof of a recent sinking of the land on the Arabian coast near the mouth of the Persian Gulf. There is evidence also of recent depression in the Delta of the Ganges and of the Mississippi, and probably in that of the Indus.

Though attended with more uncertainty, there is reason to believe,

* "Geology of India," pp. 376 and 378.

as suggested by Darwin, that great coral areas of the Indian and Pacific Oceans have long been areas of subsidence,* while adjoining volcanic areas have been areas of elevation. In some cases areas, once areas of depression, have become areas of elevation, as in the instances of some coral islands, which, though formed during periods of depression, have been since raised above the waters to heights of from 200 to 300 feet or more.

In conclusion, I may point to the imposing spectacle afforded by the slow secular upheaval of the vast tracts of Arctic lands on the shores of North America and Asia—an area of elevation so extensive that it embraces almost all the land bordering the Polar Seas. This elevation has in comparatively modern times raised the land from 100 to 400 feet above the present sea-level, and is still, in our own times, in visible action over a superficial area extending in some directions, for thousands of miles.

§ 7. *Primary Cause of Volcanic Action.*

If water only plays a secondary part in volcanic action, and the presence of the vapour of water in the volcanic foci be not the primary cause of the expulsion of the lava, to what other cause is it to be attributed? I see none but a modification of the old hypothesis, namely, that of the contraction of solid crust upon a yielding and hot nucleus. The objection to this hypothesis rested mainly on the fact that if, as was at that time assumed, the whole nucleus beneath the solid crust consisted of a molten fluid, it would be subject to tides that would lessen or neutralise the surface tides. I might also suggest as a further reason that there could be no local deformations on a continental scale:—the pressure caused by local squeezings would be dissipated through the entire mass and lost. Sir William Thomson and the late Mr. Hopkins have clearly proved that the earth possesses a rigidity perfectly incompatible with a fluid nucleus. At the same time, objections have been taken by other physicists to the hypothesis of an entirely solid globe† on the grounds, amongst others, that the question has been dealt with on the assumption of a perfect fluid, and that not sufficient allowance has been made for friction.

Nor are those views so incompatible as might at first sight appear. The questions connected with the surface tides are not yet settled. Admitting an extreme rigidity of the crust, it has not yet been proved that notwithstanding this rigidity, the crust is quite free

* This has been contested. There are no doubt instances of reefs formed without subsidence, but for the depths of the Pacific Darwin's hypothesis best answers all the conditions.

† See the various papers on this subject by Hennessy, Haughton, Delaunay, and others.

from the influence of some slight disturbances—sufficient, however, for the purposes of our contention.

For the geological argument, neither a perfectly fluid substratum nor a molten nucleus are required. The hypothesis of a central solid nucleus seems to me to be the only one compatible with geological phenomena. All that is required for the conditions of geological phenomena is that on this solid nucleus there should be a molten yielding envelope—not fluid, but viscid or plastic; nor is it necessary that it should be of any great thickness, but a thin crust is, geologically, an essential condition. The relative proportions of the two are, however, questions for physicists. The late M. Roche did attempt a solution based on the astronomical and physical conditions of the problem. Assuming the earth to consist of a solid centre with a density of about 7·0, and of an outer layer consisting of a fluid substratum with a solid crust, and having a mean density of 3·0, he found that the outer layers should have a maximum thickness equal to one-sixth of the earth's radius, or 660 miles, but he left the question of their possible minimum thickness open to other considerations.

The considerations I have already urged, in conjunction with the results of other independent physical investigations, would lead me to assign lesser dimensions to this combined thickness of the outer layers. On geological grounds the solid crust at all events need not have a thickness of even 20 miles; while, on the same grounds, the dimensions required for the underlying molten layer to place it in concordant relation with the ascertained mobility of the crust during the later geological periods, is that it should be a mass sufficiently large for the play of movements such as would come within the compass of continental (not mountain) elevations and depressions; and for this object and for the purposes of vulcanicity a molten layer, having a thickness measured not by hundreds, but by tens of miles, would fulfil the necessary conditions.

It is quite possible, as suggested by Scrope, that owing to pressure the fusion-point of lava at great depths is so much higher than at the surface, that the lava may, and possibly does, exist at depths in a viscid or plastic state, and only becomes fluid as it rises to the surface and the pressure is removed. This state of viscidity accords with the excessively slow rate of movement and steadiness of the great continental elevations and depressions,—changes in close relation one with another, and which may arise from the slow transference from one area to another of a partially resisting plastic medium within confined limits.

I cannot conceive such a transference to be effected unless that the molten layer were of moderate thickness, so that when locally compressed between the outer solid crust and the inner solid nucleus, that portion of the magma subjected to pressure would expand laterally

and the mass displaced would be transferred to that part of the adjacent area where the outer crust would yield most readily to deformation and upheaval. If the matter displaced were not confined between resisting surfaces, or if the molten layer were of indefinite thickness or of extreme fluidity, the effect would not be local, but would extend as far as the liquidity of the mass allowed of the transmission of the displaced matter, so that it would tend to become attenuated and lost in the larger volume of which it became part. The result is, in fact, a condition dependent on the measure of viscidity.

A compression in one part should, therefore, be followed by expansion in another, and by a deformation of the crust over conterminous areas. These effects are exhibited in the great continental upheavals and depressions so rife in the times immediately preceding our own, and still in a measure of perceptible action over a large part of the world; as, for example, in the instance of the slow uplifting of the northern portions of the Scandinavian and Greenland peninsulas and the subsidence of their southern portions, while further south again in Labrador the land has been rising.

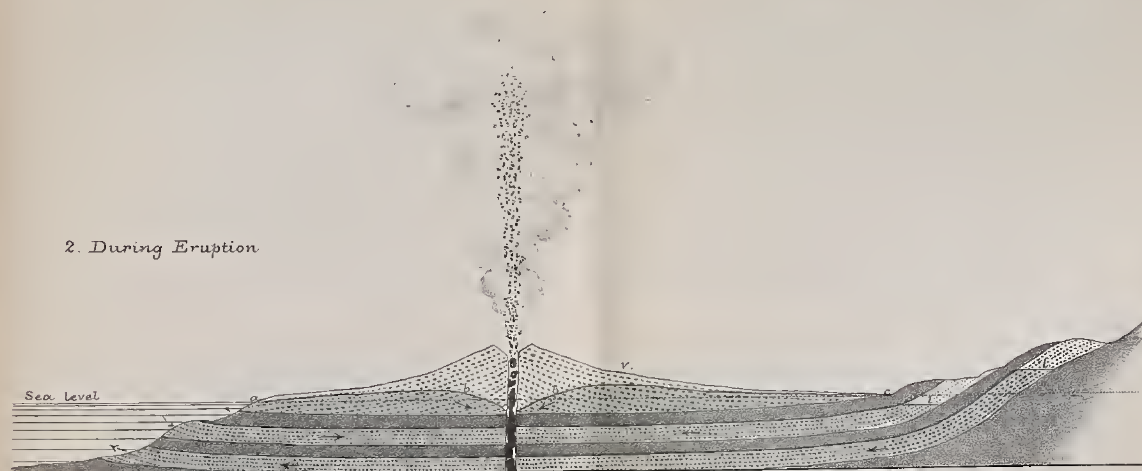
This constitutes the essential difference between the disturbances connected with mountain- and volcano-forming. They both result from the contraction due to secular refrigeration, but the one is a process of excessive lateral compression, and the other of turgid swelling of the crust, for all active volcanoes are on raised sedimentary strata. In both cases there is tension, although of a different character. In the latter it is slow, steady, and uniform in its action, and where there are permanent points of comparatively slight resistance, as in volcanic ducts, it then readily finds relief in the expulsion of the lava, which is only prolonged until the equilibrium is restored; then the eruption ceases and the volcano lapses into a state of rest, only to be broken when again there has been an accumulation of the necessary energy.

The agency of water is confined to the secondary effects I have described—effects perfectly independent of the forces which produce the extravasation of the lava; and while, with the thinner crust of former times, there would be a more frequent extrusion of the igneous rocks, there is probably, with the thicker crust of the present day and its greater resistance, larger stores of underground water and greater explosive eruptions.

In connexion with this subject, it is a noticeable fact that volcanoes, although not entirely confined to a definite zone, are far more numerous within 50° lat. N. and S. than beyond those limits, while in the northern hemisphere there are, with one exception, none beyond the Arctic circle; whereas it is beyond that circle, and where we may suppose the crust of the earth to be thickest, that the great continental movements of upheaval are now most active and maintained.

1. Before Eruption.

2. During Eruption



3. After Eruption

v Volcanic matter m Impermeable Strata P Permeable Strata Underground Waters ← Direction of Water-flow and Submarine springs.

DIAGRAM – SECTIONS OF A VOLCANIC ERUPTION

West Newman & C° lith

The lost of terrestrial heat by radiation is now exceedingly small. But small as this loss is, it cannot take place without producing contraction, and Cordier long since calculated that supposing five volcanic eruptions to take place annually, it would take a century to eject so much lava as would shorten the radius of the earth to the extent of 1 mm., or about $\frac{1}{25}$ inch.

I therefore conclude that the hypothesis originally propounded, namely, that volcanic phenomena are dependent on the effect of secular refrigeration is, with certain modifications, the one that best meets the necessities of the problem.